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The Solent Sea Breeze; Occurrence, Classification and Forecasting Aspects

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2007

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Abstract

The Solent sea breeze was studied from May-August 2006, wind speed, direction, air and sea temperature and humidity data recorded at Bramble Bank and Dockhead was provided by the hydrographer's office in Southampton. A Weather diary was also kept to identify and classify sea breeze events in conjunction with synoptic charts. The aim of the study is to record and classify sea breezes in the Solent from May – August 2006 and evaluate weather or not a previous forecast model originally for Thorney Island can be applied with any degree of accuracy at Calshot.

The Solent sea breeze was found to have a 29% occurrence over the study with the component sea breeze most frequent (36.1%), pure (27.8%), frontal (25%) and pure (11.1%) accounting for the remainder of the 36 sea breezes recorded. No one type of sea breeze was dominant in the Solent but observations backed up the idea of a double effect in the area with 61.2% of sea breezes approaching from the west and 38.8% the east with the high ground of the Isle of Wight blocking any approach from the south. The magnitude of the air-sea temperature difference had no bearing on the time of onset but did seem to effect which type of sea breeze formed with frontal, pure, component and pseudo sea breezes needing average air-sea temperature difference of 4.9, 3.8, 2.9 and 2.9°C respectively. Once re-orientated to Calshot, the forecast model was found to be 57% accurate at predicting time of onset to within an hour and 75% to within 1½ hours of actual occurrence.

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1.0. Introduction

1.1. The Sea Breeze

The sea breeze is a meso-scale air circulation that occurs in coastal areas around the world; in the mid latitudes sea breezes are most common during the spring and early summer from April to July where the temperature difference between the land and sea is greatest (figure 1.0) but may occur any day of the year where a sufficient temperature gradient exists.. Sea breezes are driven and maintained by a temperature difference between cool sea air and warmer air over land, the temperature gradient causes a decrease in pressure over land relative to the sea and consequently air flows onshore. Convection arises as a result of overland air heating and subsidence from air cooling over the sea, the circulation is maintained by a return current carrying air out to sea above the onshore surface flow.

Sea breezes have been studied heavily around the world and although the mechanisms which drive them remain constant, numerous other factors affect the formation, strength, direction and duration of a sea breeze giving them strong local characteristics specific to their geographic location.

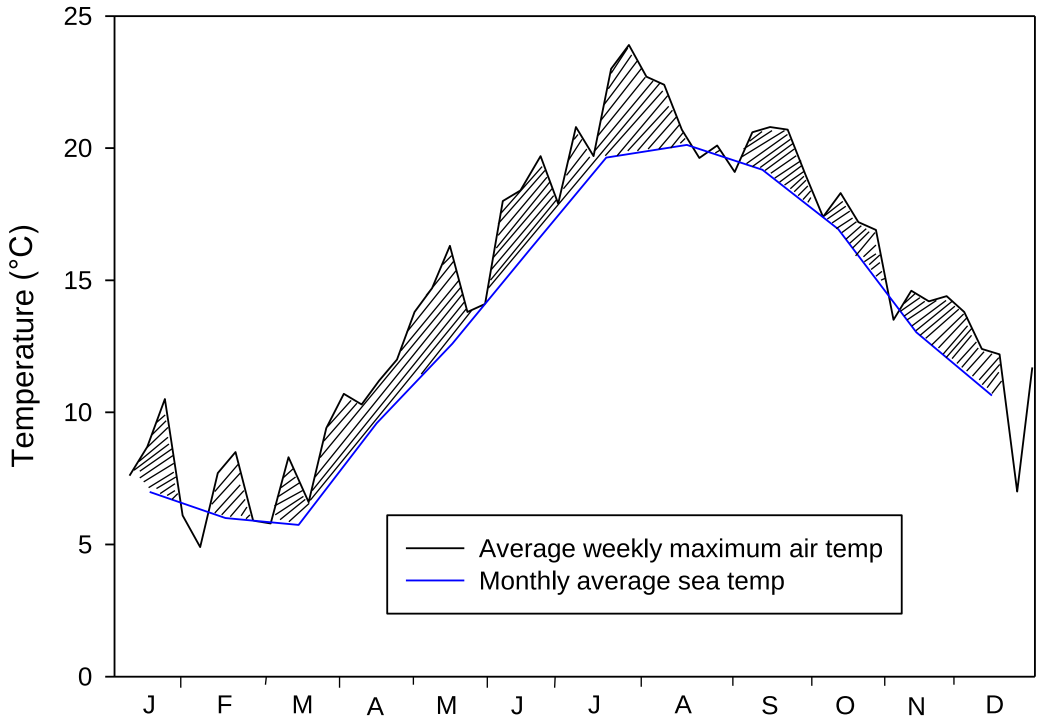


Figure 1.0. Probability of sea breeze occurrence, annual differences in air and sea temperature, shaded regions indicated where sea breezes are possible.

1.2. Significance of the Study

The study of the sea breeze is important for a number of reasons, in areas where commercial shipping and recreational water users operate in a confined space, knowledge of local variability in the weather conditions could have significant impact of navigational decisions made. Similarly for aviation, where airfields exist in coastal areas, arrival of the sea breeze may prompt landing issues, in which case another runway might be selected. Observational studies of the sea breeze in one location for a period of time allow a picture to be built up of the localised effects on the sea breeze and can contribute towards identifying favourable conditions for sea breeze occurrence.

1.3. Aim and Objectives

The aim of this study is to monitor record and classify the occurrence of sea breezes in the Solent during the months May, June, July and August 2006.

The main objectives in support of this aim are:

1. Apply Watt's (1955) model for forecasting time of onset of sea breeze at Thorney Island to Calshot.

2. To show the frequency of sea breeze occurrence in the Solent in relation to the synoptic situation, state of tide or temperature inversions.

3. To determine if any particular type of sea breeze is dominant in this area by classification into four clear groups as shown in Table 1.0.

2.0. Theory and Review

2.1. Factors Affecting Sea Breeze Development.

2.1.1. The Gradient Wind

The advection of air during the morning and early afternoon can have a significant effect on the maximum temperature and humidity reached over land and, therefore the rate of convection and pressure change. It is the convection of air over land and the resultant pressure change that forms the mechanism driving the sea breeze and so it is relevant to review where the air comes from or what happens under calm conditions.

2.1.2. Offshore Gradient Wind

Many authors have favoured an offshore gradient wind for most likely formation of a sea breeze. The offshore gradient wind carries warm air out over the sea where it forms a sea breeze front which slowly advances towards the coast and inland. Brittain (1966) stated that in offshore conditions the maximum wind beyond which a sea breeze will not develop is $8ms^{-1}$ regardless of the temperature difference. Fig 2.0 shows formation of a sea breeze in offshore gradient wind conditions. Firstly the sun heats the land and causes the pressure to rise at B, column AB becomes warmer and the pressure rise at B causes more wind to blow out to sea from B to C than the existing gradient wind. This results in a fall in pressure at A and rise at C, subsidence causes the pressure to rise at D relative to A, the PGF DA is the sea breeze. As inland heating continues it strengthens the circulation and the sea breeze front progresses inland at a velocity of approximately half the maximum surface wind associated with it, Pearce, (1965).

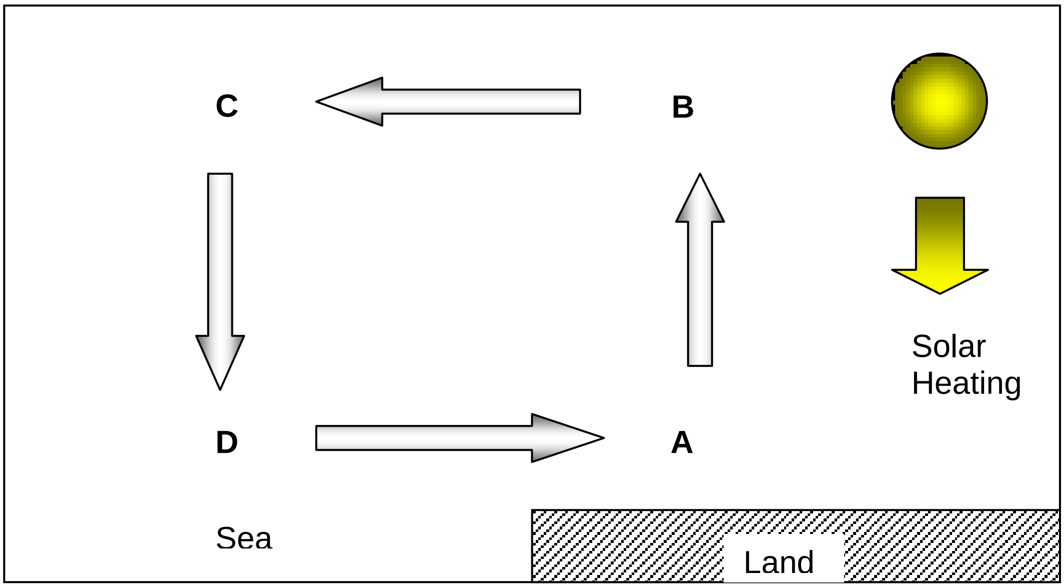


Fig 2.0 Sea breeze formation in offshore conditions.

2.1.3. In Calm Conditions

Figure 2.1 illustrates how as the day progresses, the temperature difference increases causing column A to expand and lower in pressure. A pressure difference now exists between A and B, cooler moist air is then drawn in from column B by the pressure gradient force (PGF) between the two. The greater the effect of heating the greater the PGF produced, the sea breeze is often strongest just after the period of maximum heating inland mid afternoon. Sea breeze circulations are relatively shallow when compared to synoptic scale weather systems often only extending 1 - 1.5km vertically and several hundred km horizontally (Mathews, 1982).

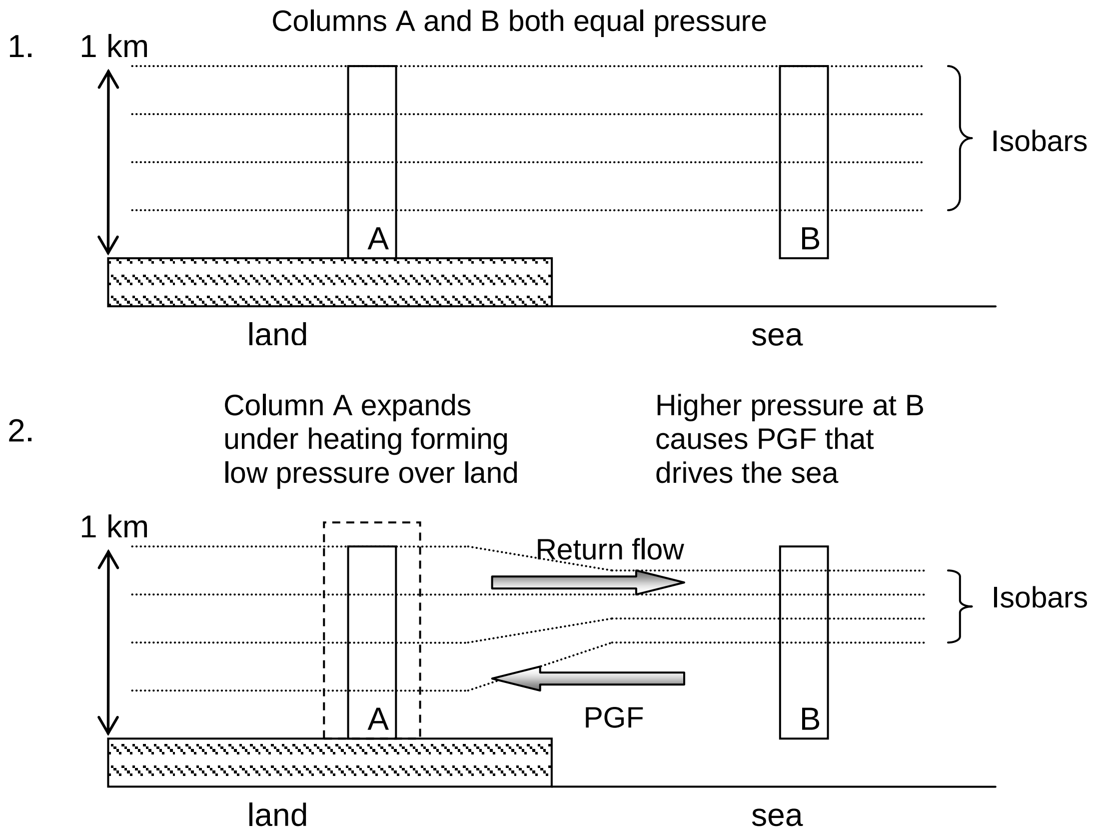


Fig. 2.1. Sea breeze formation under calm conditions. Adapted from Simpson, (1994)

2.1.4. Onshore or Crosshore Gradient Wind

Formation of a sea breeze is still possible when the wind is blowing either onshore or alongshore. On these days the sea breeze is a result of the general wind component and the sea breeze wind component and as a result the change in the wind field when the sea breeze arrives will only be small (20 - 40°) and difficult to detect. (Hope-Hislop, 1974)

2.1.5. Topography

Other local features have also been documented to have an effect of the sea breeze include the orientation of the coastline; a southerly facing coast will receive more solar radiation than one facing north and so heat at a greater rate. The topography of the surrounding land is one of the factors that make sea breezes in one location completely different to others, Peters (1938) states that few circulations extend above 300m in the British Isles, this effect has been studied in a numerical model by McPherson (1970) who found significant deflections in the three dimensional flow in a square shaped bay with mountains surrounding, a convergence zone that was observed in the west of figure 2.2 was thought to be a result of the coriolis and overall pressure force acting in the same direction on one side of the bay and in the opposing direction on the other side.

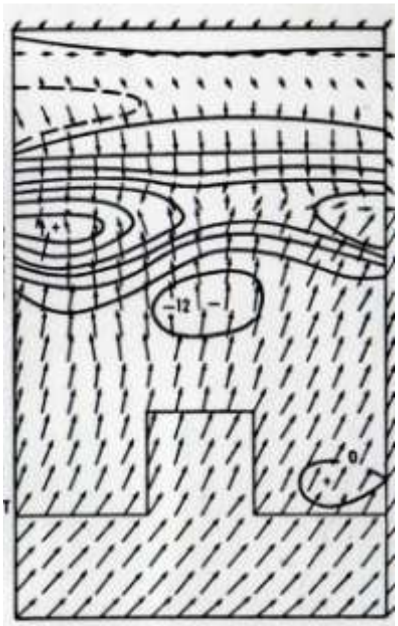


Figure 2.2. Convergence zone (top left of picture) observed by McPherson (1970)

<u>2.1.6. Synoptic Situation</u>

The strength and direction of a sea breeze is dependant upon several factors, the synoptic scale weather situation at time of onset, (Damato *et al*, 2003) including the gradient wind speed and direction, also cloud cover Defant, (1951) highlights the relationship between cloudiness and sea breeze probability, giving a 90% probability of sea breeze formation when cloud cover is 0 – 50%. Sumner, (1977) states that the highest incidence of sea breezes occurs during stable anticyclonic spells and for continental air masses, extremely unstable air masses tend to encourage such strong vertical air motion that any incipient sea breeze development is totally swamped. However Pearce, (1965) and later Brittain, (1978) found that stable air dampens vertical circulation within the sea breeze cell and that unstable air enhances both the vertical and horizontal circulation. These conflicting statements reflect the strong local character of the sea breeze.

2.1.7. The Coriolis Force

The earth's rotation gives rise to an apparent force that acts upon fluids and all moving objects called the coriolis force, the coriolis force causes a deflection, to the right in the northern hemisphere and the left in the southern hemisphere. The effect of the deflection is magnified with increasing latitude, highest at the poles and decreasing to zero at the equator. (Ahrens, 2003). The Coriolis Effect is most prominent in the mid-latitudes where longer daylight hours in the summer result in more insolation producing a bigger deflection. Higher forces are experienced at the poles but insolation is low and conversely high insolation at the equator has little effect on the deflection as here the force tends towards zero, in the mid-latitudes (in the northern hemisphere) the Coriolis Effect may be observed by an added veering component to the sea breeze throughout the day.

2.1.8. Cloud Formation and Cover.

The sea breeze is less likely to form on days where cloud cover is high (Hope –Hislop, 1974) states that over $^{4}/_{8}$ cloud cover will inhibit sea breeze formation by reducing the amount of insolation able to reach the land surface and be used for heating, with the rest being adsorbed or reflected by the clouds themselves.

Cumulus cloud formation has been documented by many authors (Brittain, 1966 and Pepperdine, 1966) as beneficial to sea breeze development as they are a sign of convection, however other authors whose research was primarily conducted in the area concerned (Simpson, 1966) agreed that while convection was required a high cloud base and dry atmosphere were more favourable conditions.

2.1.9. Temperature Inversions

On a day that is very warm yet cloudless, sea breezes may be hindered by inversions of temperature which dampen any large scale convection currents, (Watts, 1987). The presence of a temperature inversion may be noted by observing smoke rising from a stack, the smoke rises only to a certain height before it stops in mid-sky and rises no further; instead it starts to disperse horizontally. This happens because the air above is warmer and denser so the rising smoke must find another way around.

2.1.10. Presence of Sand and Mudflats in Bays/ Estuaries

Watts, (1955) states that in area where large mud flats are present the state of tide has an effect on sea breeze formation either reinforcing the circulation or opposing it depending on the time of each tide. Watts observed that there was a marked difference between in shore and mid-channel temperatures around Thorney Island an area surrounded by wide tidal mud and sand flats, he found that water that had just recently drained off of the mud flats around the thermometer was up to 10°F warmer than the preceding high tide. In the first instance where flood tide water is warmed by flowing over mud heated in the sun during the summer, the following ebb tide will then warm the inshore waters, reducing air sea temperature difference and hindering sea breeze development, this effect would have greatest effect in the summer when high tides are around midday. In the second instance with a high water around

09:00 GMT waters will come in contact with the nocturnally cooled mud lowering inshore water temperatures combined with a day of high insolation the sea breeze may be enhanced. This effect is most likely to occur during the spring where the nights are adequately long for cooling to take place. (Wood, 1999)

2.2. Classification of Sea Breeze Events

As a number of different types of sea breezes occur it is necessary to classify them, this can be done by the differences in the nature of their onset shown in Table 1.0.

Temperature Change	Change in Wind Speed	Change in Wind Direction	Sea Breeze Type
Sharp decrease	Sudden	≈ 180°	**FRONTAL**
General Lowering	Gradual	20-40°	**COMPONENT**
Truncated	Gradual	Calm to start	**PURE**
General Lowering	General Increase	No or very little change	**PSEUDO**

Table 1.0. Adapted from Hope-Hislop (1974)

2.2.1. The Frontal Sea Breeze

Frontal sea breezes are characterised by a sharp decrease in air temperature and rise in humidity, with the gradient wind blowing offshore and most commonly swinging through 180° a frontal sea breeze can also occasionally be identified by a line of cloud parallel to the coast on an otherwise cloudless day called the sea breeze front. (Simpson, 1994)

2.2.2. The Component Sea Breeze

Component sea breezes show an overall lowering of air temperature rather than a sharp decrease as observed with a frontal sea breeze. Component sea breezes rarely have frontal characteristics such as temperature and humidity jumps and are generally distinguished by a small change in the wind field of 20-40°. Component sea breezes usually blow from the SE sector, (Hope-Hislop, 1974).

2.2.3. The Pure Sea Breeze

Pure sea breezes occur when the sea breeze onsets into a calm wind field at the Earths surface. The temperature difference required to generate a pure sea breeze is relatively small (2-4°C) and the resulting temperature change at onset is correspondingly small. (Hope-Hislop, 1974) The wind field in a pure sea breeze will generally orientate itself normal to the coastline with a steady increase in wind speed until after the period of maximum heating inland. The sea breeze begins to abate as solar heating decreases and friction dissipates the motion.

2.2.4. The Pseudo Sea Breeze

The pseudo sea breeze is the least documented of all, as the name “pseudo” means something that’s not really there they are typically hard to identify from records as the changes in the wind field are not particularly marked with the sea breeze component adding to the gradient wind with little or no change in direction and a general lowering in air temperature that may be consistent with increased wind speeds.

2.3. The Solent: Location

The Solent is located in central southern England and is the body of water extending west to the Needles on the Isle of Wight and East towards Selsey Bill, met in the middle by Southampton water, much of the western Solent is enclosed and sheltered by the high ground around Totland and the Needles on Isle of Wight to the South, the eastern side of the island is comparatively flat. A flat, lightly forested heath land exists inland beyond the western Solent and the relatively high southerly facing slopes of the South Downs inland beyond the Eastern Solent as shown in figure 2.3. The Solent is a macro-tidal environment (mean spring range = 4m) and due to its position in an estuary the input of fresh water distorts the tide, a double high water is experienced in the Solent with a long rise and short fall (George, 2003) Due to the relatively large tidal range much of the inter-tidal zone becomes exposed at mid to low tide revealing large areas of sand and mudflats.

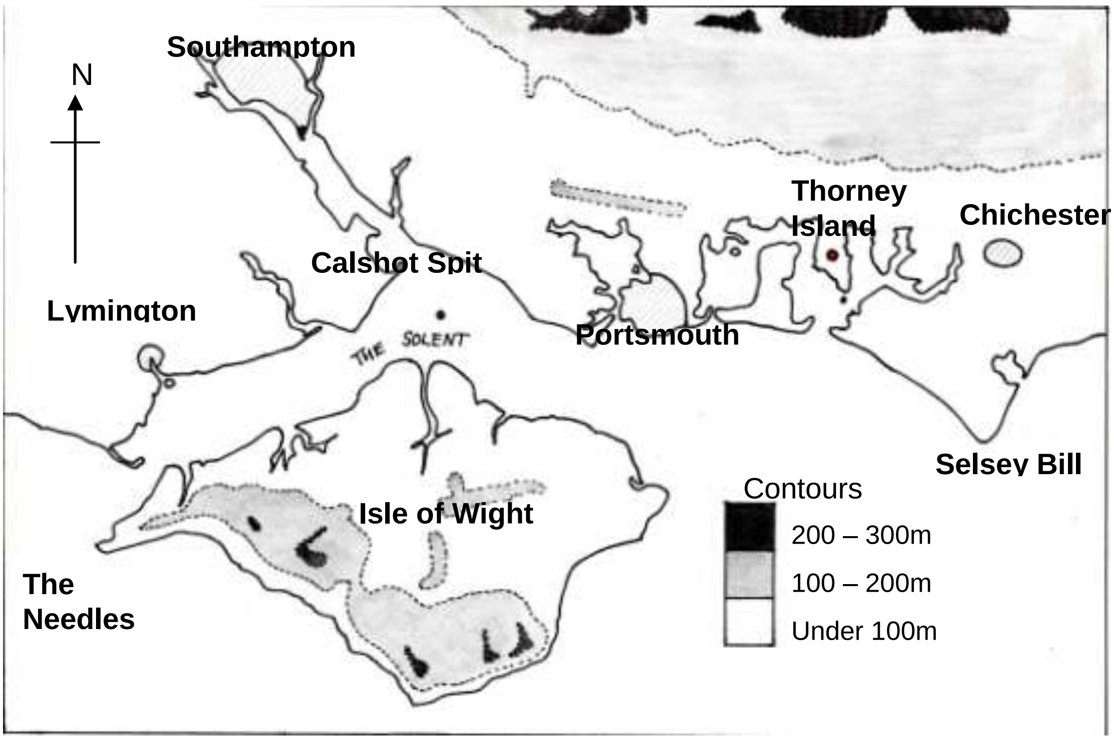


Figure 2.3. Map of the Solent and its surroundings. Adapted from Watts (1955)

2.4. Previous Work in the Solent

There has been much research conducted in and around the Solent, Watts, (1955) examined the sea breeze at Thorney Island for 3 years producing a model to predict the time of onset of the sea breeze at Thorney Island when gradient wind conditions were offshore, this was successful in predicting the time of onset within 1hour of the observed time on 69% of occasions. Other research in the area tends towards measuring a particular sea breeze event and tracking its inland penetration. Wallington (1959) used gliding flights to reveal the vertical extent of a sea breeze, the speed of advance of a sea breeze front and wind velocities either side of the front. Simpson (1964) used hourly pressure charts from the met office to observe the development of a pressure pattern and so the sea breeze. Simpson (1967) used aerial and radar observations. Simpson *et al*, (1977) studied sea breeze penetration as a function of the tide for a period of 12 years at Lasham, they revealed sea breezes were most likely to occur when high tide at Hayling Island is between 10:00 and 16:00 GMT. These findings were attributed to the large area of sand and mudflat at Thorney Island that the sea breeze must pass over. The situation is similar at Calshot, a large gravel spit with vast areas of salt marsh and mudflat to the North on both sides of Southampton Water. Burton, (2000) tracked each event using weather stations dotted across the south coast. Damato, *et al* (2003) used remote sensing to study the extent of inland penetration across the English Channel in both the UK and France concluding that typical penetrations in the UK range from 10 – 50km inland, with penetration found to be dependant upon the coasts topography and exposure, however sea breezes have been documented to reach up to 100km inland. (Simpson, 1994)

Watts (1987) documents the Solent sea breeze as having a double effect depending on the direction of the gradient wind, the sea breeze will flow up either the East or West Solent either side of the Isle of Wight. A prevailing wind with a westerly component can be influenced by the Isle of Wight's topography with the high land around Totland and the Needles directing the sea breeze flow around the island causing the wind to compress and locally between Lymington and Calshot it is not uncommon for the wind to increase from force 4 to force 6, where other areas in the Solent such as Thorney Island continue to experience force 4, this could be a result of the venturi effect. Mountains and high terrain have been confirmed to interact with and modify sea breezes in similar ways most notably by Peters, (1938), McPherson, (1970) and Kikuchi, (1981) who state that few circulations extend above 300m in the British Isles.

Watts (1987) goes on to state that when the winds prevail from the east they tend to dissipate their energy over the eastern Solent around Portsmouth and up Southampton Water, while the western Solent experiences a lesser affect with marked differences between places as close as Calshot and Lee on Solent. Watts outlines three general rules to help sailors try to read the sea breeze from conditions on the day, he goes on to state that in light wind conditions with big scattered cumulus clouds the sea breeze will arrive quickly and penetrate along way inland. Small puffs of cumulus over the hills indicate that the sea breeze will neither be hindered nor greatly helped and if it is warm and there is a layer of cloud in the morning that "burns off" the arrival of the sea breeze will be slow and possibly erratic.

2.5. Watts Forecasting Model

Watts (1955) came up with a model for forecasting the sea breeze at Thorney Island in the eastern Solent, after studying the sea breeze there for several years he was able to plot graphs of the maximum temperature difference against time of onset, there was a clear separation between marginal events and when a sea breeze did actually occur. The Wind components were broken up into 5 smaller offshore sectors between 280 - 89˚. The offshore wind speed at 900m (3000ft) was plotted against time of onset with similar findings to the temperature difference, completing the model. The following steps needed to be taken to forecast the sea breeze at Thorney Island:

i) Obtain the maximum expected land temperate

ii) Obtain the forecast upper wind speed and direction.

iii) Choose a diagram from figure 2.4 corresponding to points i) & ii) and plot against one another – read off the graph weather the sea breeze is probable, marginal or improbable.

iv) If likelihood is probable or marginal then using forecast upper wind speed and direction read off forecast time of onset from the appropriate diagram in figure 2.5

v) If the air stream is stable expect average period of transition from gradient wind to the sea breeze, if unstable expect a sharp change from the gradient to sea breeze direction.

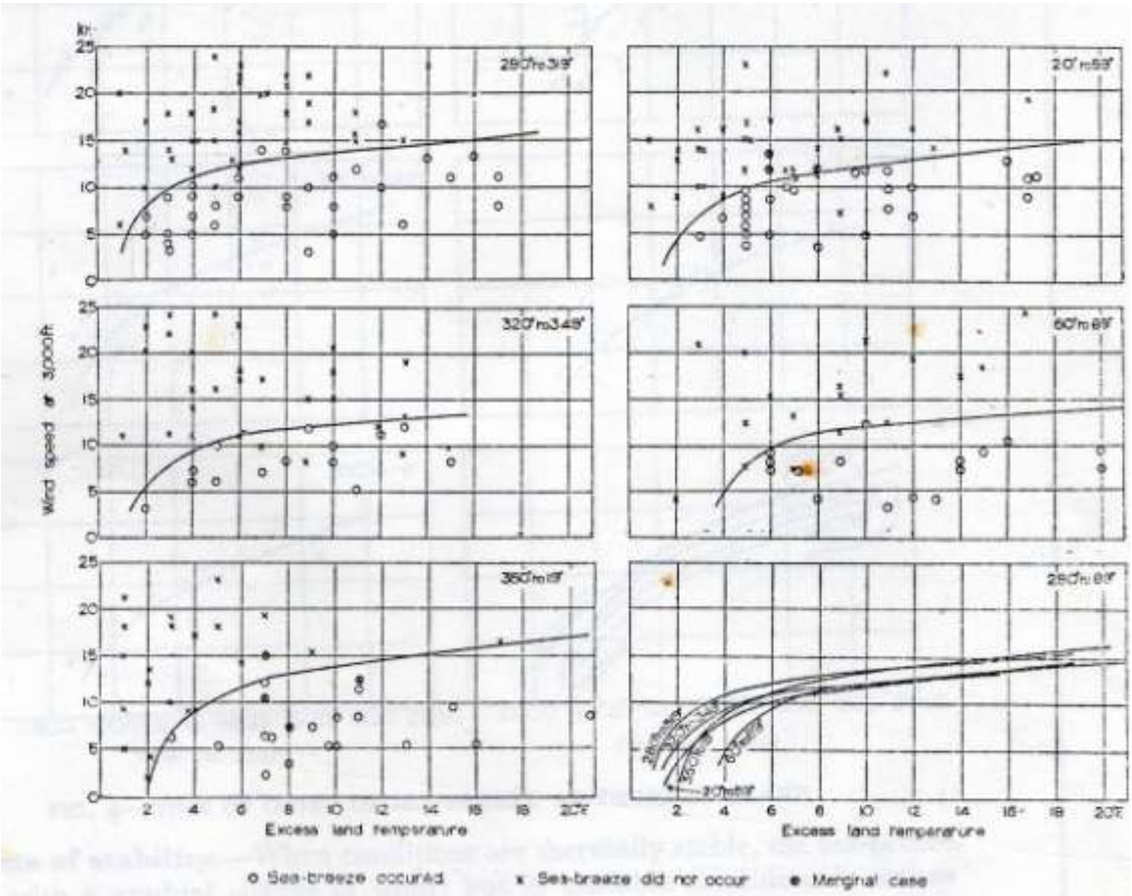


Fig 2.4. Stage iii) of Watts forecast model for Thorney island (1955)

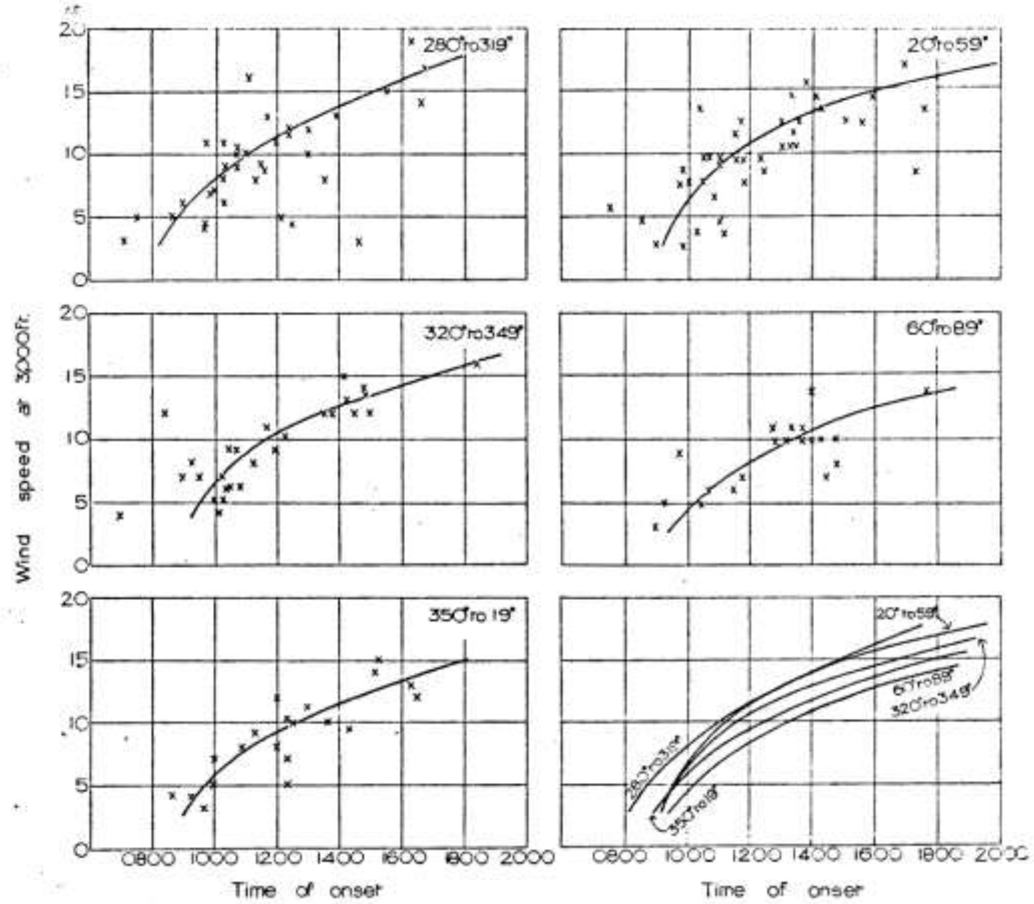


Fig 2.5 Stage iv) of Watts forecast model for Thorney Island (1955)

3.0. Methodology

3.1. Data Collection

The study will be completed using reliable secondary data provided by the senior hydrographer at Associated British Ports (ABP) in Southampton; the data comes from two recording stations in the Solent shown in figure 3.0, Dockhead and the Bramble Bank. The Bramble bank station will provide data on wind speed (in knots), wind direction (degrees from North) and air and sea surface temperatures (in °C). The Bramble weather station doesn't have a hodograph so humidity data will be used from the Dockhead station about 2 miles north from Calshot where the river Itchen joins Southampton Water at 47m above sea level. Data is recorded at 10 minute intervals on both stations; this will give sufficient resolution in results to make the arrival of a sea breeze discernable.

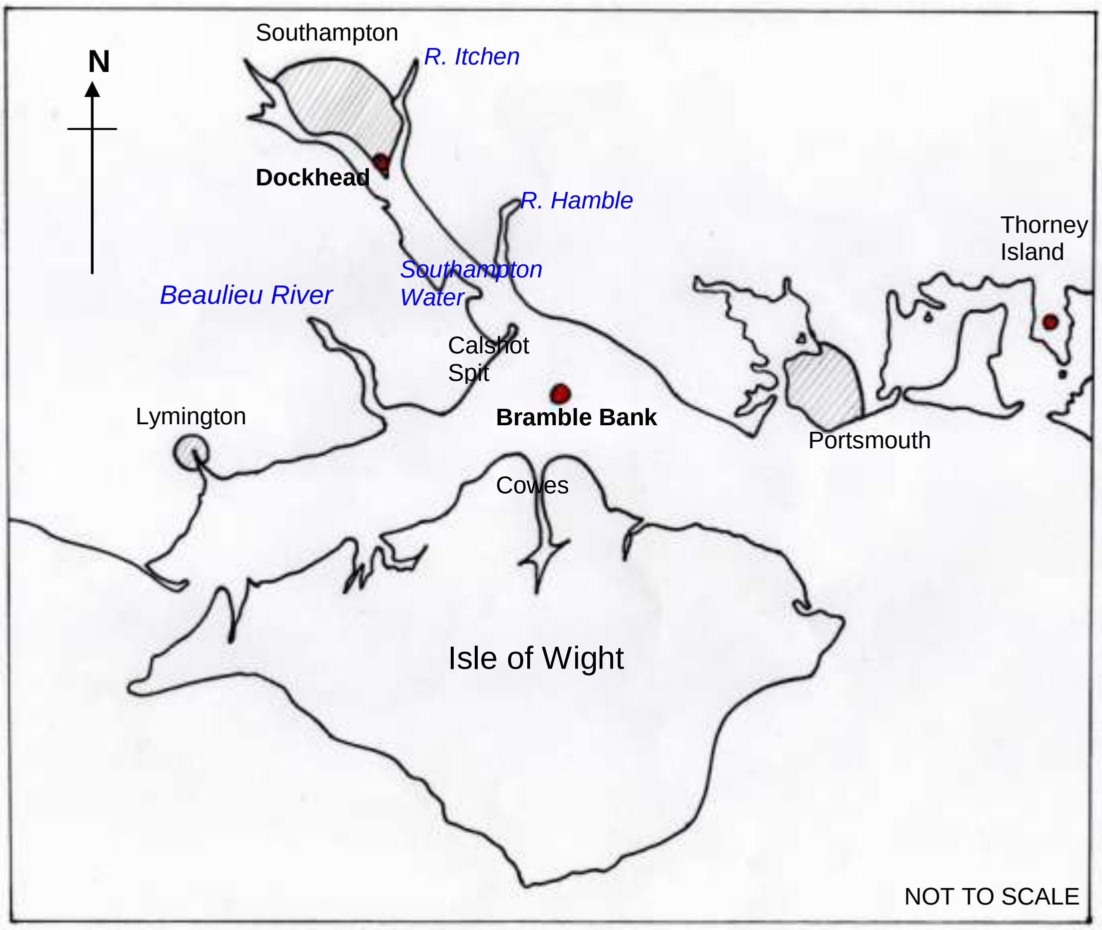


Figure 3.0. Location of Bramble and Dockhead recording stations

The centrality of the bramble recording station in the middle of the Solent is particularly relevant especially when trying to distinguish between sea breezes flowing up either the east or western Solent, Also the location means that there is little interaction from buildings and readings of the wind will be true and not distorted.
Synoptic weather charts will be used along with a daily diary compiled over the duration of the study to confirm the occurrence of a sea breeze and ensure that the onset is not seen as the front of a larger scale weather system passes over the station.

NOAA satellite images have been examined where frontal sea breezes occur for associated features such as the sea breeze front which can be seen as a relatively straight band of cloud advancing inland with clear skies sea ward of the front.

3.2. Identification of Sea Breezes

The arrival of a sea breeze is not always simple to identify as each type of sea breeze onsets in a different way. The main indicators that are used to mark the arrival of the sea breeze are changes in temperature and humidity that match changes in the wind field. Humidity as an indicator of the sea breeze can only be used reliably when the gradient wind is offshore and sometimes calm, the invasion of a sea breeze will be marked by a rise in humidity accompanied by a drop in temperature as the cooler more moist sea air is drawn in over the land, this is nearly always discernable on records, see figure 3.1. (Hope-Hislop, 1974)

Sea breezes will be identified by plotting graphs of wind speed, wind direction, air and sea temperature and humidity (where appropriate) and relating changes in conditions to Table 1.0 to classify each event. If there is any doubt as to weather a sea breeze occurred that event will be omitted from results.

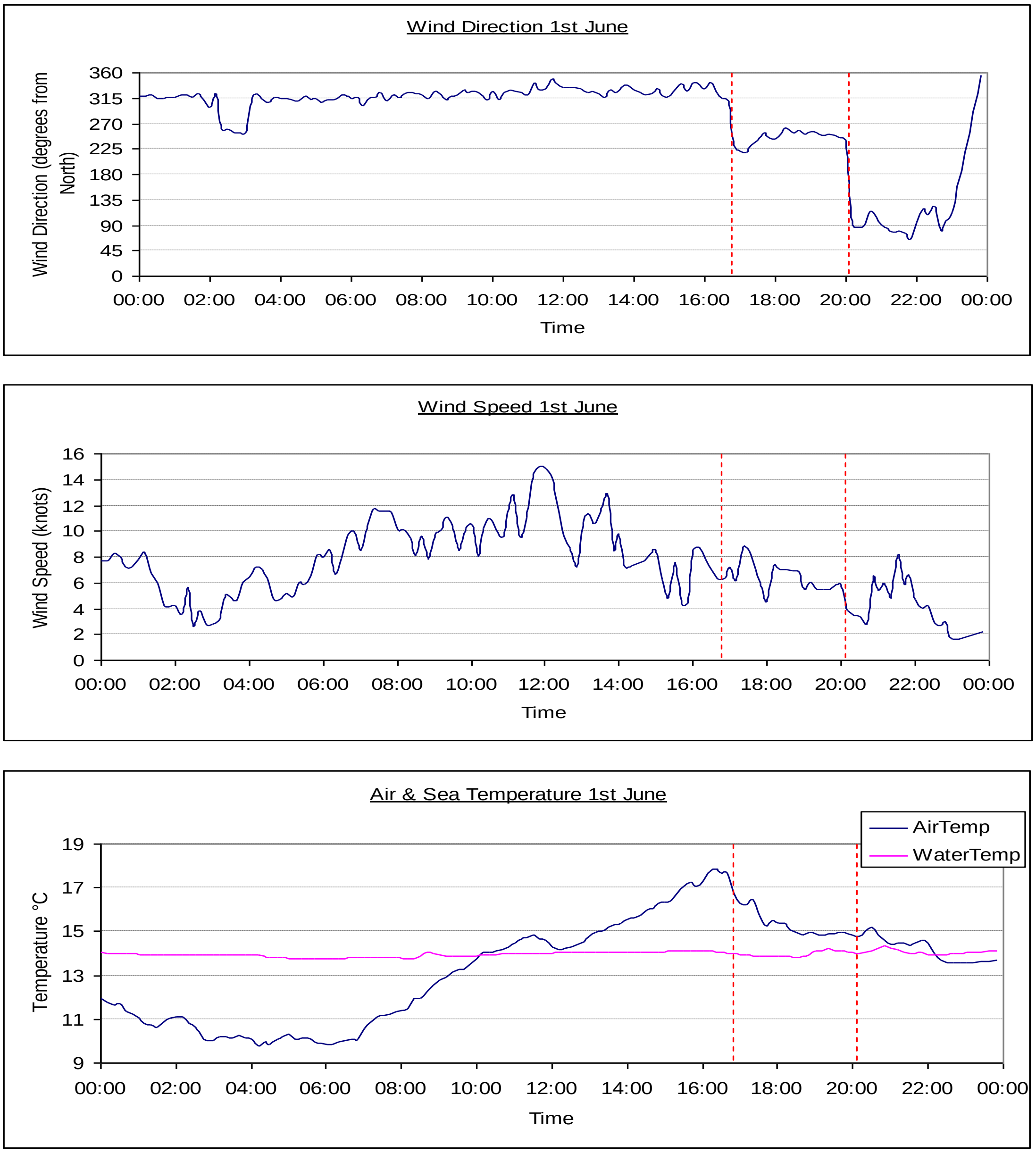


Figure 3.1. Use of records to identify a sea breeze. Time of onset shown as 16:50 by red dotted line.

3.3. Watts' Forecast Model

Only surface wind speeds have been recorded near Calshot which are likely to be slightly lower than those at 900m (3000ft) due to the effects of friction within the boundary layer. The model will be tested using geostrophic wind speeds from met office synoptic charts and the surface direction. The wind sectors have been modified to suit Calshot's orientation to the coastline but still keeping the same spread and equal sized sector.

3.4. Reorientation of Watts' model to Calshot.

Watts uses a spread of 169° to cover the offshore wind directions at Thorney Island, the same spread will be used for Calshot but incorporated wind directions (the offshore sector) must be reoriented to suit the coastline at Calshot (figure 3.2). The sectors (1-5) from watts model have been reorientated in Table 2.0.

Offshore sectors at Thorney Island	Sector	Offshore sectors at Calshot
280 - 319°	1	231 - 270°
320 - 349°	2	271 - 300°
350 - 19°	3	301 - 330°
20 - 59°	4	331 - 10°
60 - 89°	5	11 - 40°

Table 2.0. Re orientation of offshore wind sectors in Watts forecast model for Thorney Island

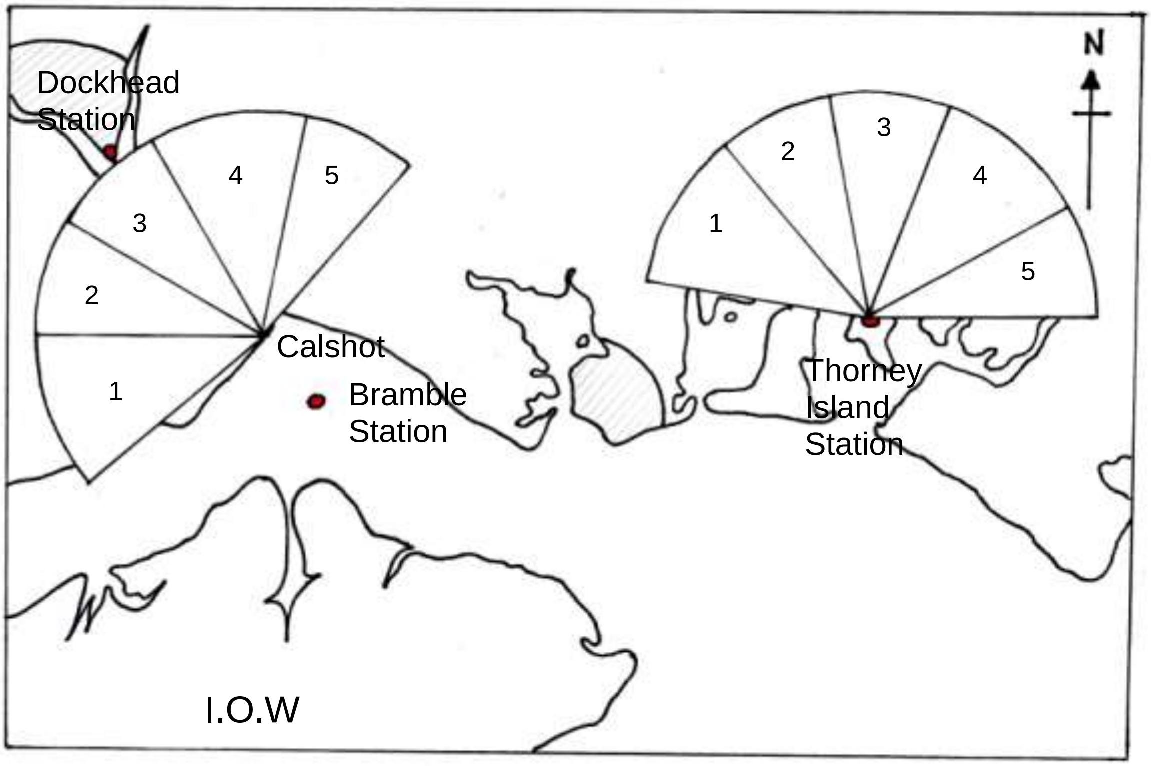


Figure 3.2. Re orientation of offshore wind sectors at Calshot.

4.0. General Results

The period of study lasted 123 days, in which there was 29% sea breeze occurrence, all 36 events are documented in Table 3.0.

The component sea breeze was found to be the most frequent type of sea breeze found in the Solent accounting for 36.1% of all sea breeze events (figure 4.0), followed by pure sea breezes which accounted for 27.8%, closely followed by the frontal type accounting for 25%. The Pseudo sea breeze was found to be the least frequent type of sea breeze in the Solent with only 11.1% occurrence.

The most frequent direction of the gradient wind before onset (figure 4.1) was the westerly sector (27%) NW, N and NE all had a 15% occurrence with frequency of occurrence decreasing the further onshore the wind swung easterlies and south westerly were each experienced before 11.8% respectively of sea breezes, only 3.8% when the wind blew from SE and no sea breezes were observed when the gradient wind blew from the south.

The percentage frequency of all observed sea breeze directions (figure 4.2) mirrors results shown in figure 4.1, the majority of gradient winds observed before sea breeze events were from the W and SW sectors, the same is true for the observed sea breeze direction, 61.2% of all sea breezes during the study period blew from either W or SW (22.2% and 39% respectively) the remaining 38.8% of sea breezes blew from the E or SE sectors agreeing with Watts observations (1987) that the Solent sea breeze has a double effect as the Isle of Wight provides two channels for the sea breeze to flow as high ground blocks and approach from the south.

The time of onset of all sea breezes recorded is very spread (figure 4.3) 88.8% of all events (36 in total) onset between 09:00 and 14:59 suggesting that this is the most likely period for sea breezes to form. Sea breezes onset most frequently from 11:00 – 11:59 (22.2%).

Time of abatement (figure 4.4) looks slightly more organised with 77.7% of all sea breezes abating between the hours of 16:00 and 19:59 after the period of maximum heating during the day has passed. On very hot days some sea breezes blew until 21:00 while on cooler days abated by 13:00. Duration of all sea breezes is shown in figure 4.5.

Date	Gradient wind		Sea Breeze		Windfield Change		Time	Time	SB	Max Air: Sea	Sea Breeze
	Speed	Direction	Speed	Direction	Speed	Direction	of	of	Duration	Temperature	Type
	(knots)	(degrees)	(knots)	(degrees)	(knots)	(degrees)	Onset	Abating	(hours)	Difference °C	
01/05/06	15.1	262.3	15.3	234.1	0.2	-28.2	14:40	16:50	02:10	2.1	COMPONENT
03/05/06	8.2	228.4	7.4	105.2	-0.8	-123.2	16:10	20:20	04:10	2.5	FRONTAL
09/05/06	6.4	273.5	10.6	235.4	4.2	-38.1	09:30	19:50	10:20	0.9	COMPONENT
10/05/06	6.7	332.6	10.3	223.9	3.6	-108.7	12:10	19:40	07:30	7.9	FRONTAL
11/05/06	1.5	72.3	4.5	123.2	3	50.9	09:50	18:20	08:30	5.9	FRONTAL
12/05/06	1.6	16.1	8	102.7	6.4	86.6	11:00	18:40	07:40	2.9	FRONTAL
13/05/06	8.1	259.7	16	241.3	7.9	-18.4	11:40	19:30	07:50	2	COMPONENT
16/05/06	4.6	211.6	5.8	224.9	1.2	13.3	11:40	16:00	04:20	2.6	PSUEDO
25/05/06	6.3	235.4	11.9	241	5.6	5.6	12:00	17:30	05:30	2	PSUEDO
01/06/06	8.2	319.04	6.35	238.1	-1.85	-80.94	16:50	20:10	03:20	3.77	FRONTAL
02/06/06	6.36	13.87	8.81	251.04	2.45	237.17	12:40	16:00	03:20	5.51	FRONTAL
03/06/06	4.45	307.44	7.11	235.49	2.66	-71.95	14:20	17:30	03:10	7.72	FRONTAL
04/06/06	3.52	130.73	9.22	250.54	5.7	119.81	11:20	18:40	07:20	5.7	COMPONENT
07/06/06	1.8	275.19	11.06	250.39	9.26	-24.8	10:00	19:00	09:00	1.23	COMPONENT
09/06/06	6.32	112.15	15.76	105.76	9.44	-6.39	09:00	21:00	12:00	4.63	PSUEDO
13/06/06	4.93	315.82	7.8	249.03	2.87	-66.79	09:30	12:30	03:00	2.94	COMPONENT
16/06/06	5.28	253.44	9.52	247.73	4.24	-5.71	12:10	17:30	05:20	1.75	PSUEDO
17/06/06	0.93 **CALM**	N/A	6.98	249	6.98	249	09:30	17:30	08:00	2.51	PURE
18/06/06	0.81 **CALM**	N/A	7.94	247.68	7.94	247.68	11:50	18:20	06:30	5.18	PURE
24/06/06	0.06 **CALM**	N/A	7.18	243.79	7.18	243.79	13:30	17:10	03:40	1.83	PURE
25/06/06	0.91 **CALM**	N/A	5.09	108.6	5.09	108.6	11:30	15:20	03:50	1.68	PURE
01/07/06	1.42	52.32	8.63	112.4	7.21	60.08	06:40	19:00	12:20	3.13	COMPONENT
03/07/06	3.91	340.14	7.37	113.89	3.46	-226.25	09:40	19:40	10:00	6.41	FRONTAL
04/07/06	0.79 **CALM**	N/A	7.16	111.56	7.16	111.56	10:50	14:10	03:20	4.4	PURE
11/07/06	9.32	279.15	14.85	235.35	5.53	-43.8	14:40	19:20	04:40	1.43	COMPONENT
15/07/06	9.46	55.45	10.1	114.88	0.64	59.43	13:40	17:30	03:50	3.55	COMPONENT
16/07/06	3.04	80.43	6.37	113.03	3.33	32.6	14:10	18:30	04:20	4.79	COMPONENT
17/07/06	0.67 **CALM**	N/A	5.35	117.82	5.35	117.82	12:30	16:00	03:30	6.81	PURE
18/07/06	0.23 **CALM**	N/A	8.97	115.94	8.97	115.94	10:20	21:10	10:50	5.88	PURE
19/07/06	0.33 **CALM**	N/A	14.07	124.78	14.07	124.78	09:30	14:30	05:00	4.46	PURE
25/07/06	2.06	38.16	11.17	107.46	9.11	69.3	06:50	17:10	10:20	2.38	COMPONENT
27/07/06	0.05 **CALM**	N/A	14.62	248.43	14.62	248.43	14:20	19:00	04:40	2.37	PURE
05/08/06	6.44	349	10.73	233.64	4.29	-115.36	11:50	18:40	06:50	0.41	COMPONENT
06/08/06	0.42 **CALM**	N/A	12.18	242.08	12.18	242.08	11:20	18:00	06:40	2.76	PURE
08/08/06	4.53	48.98	16.62	231.97	12.09	182.99	13:50	19:00	05:10	1.66	FRONTAL
27/08/06	8.5	268.98	16.67	238.23	8.17	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Table 3.0. General results for all observed sea breeze events.

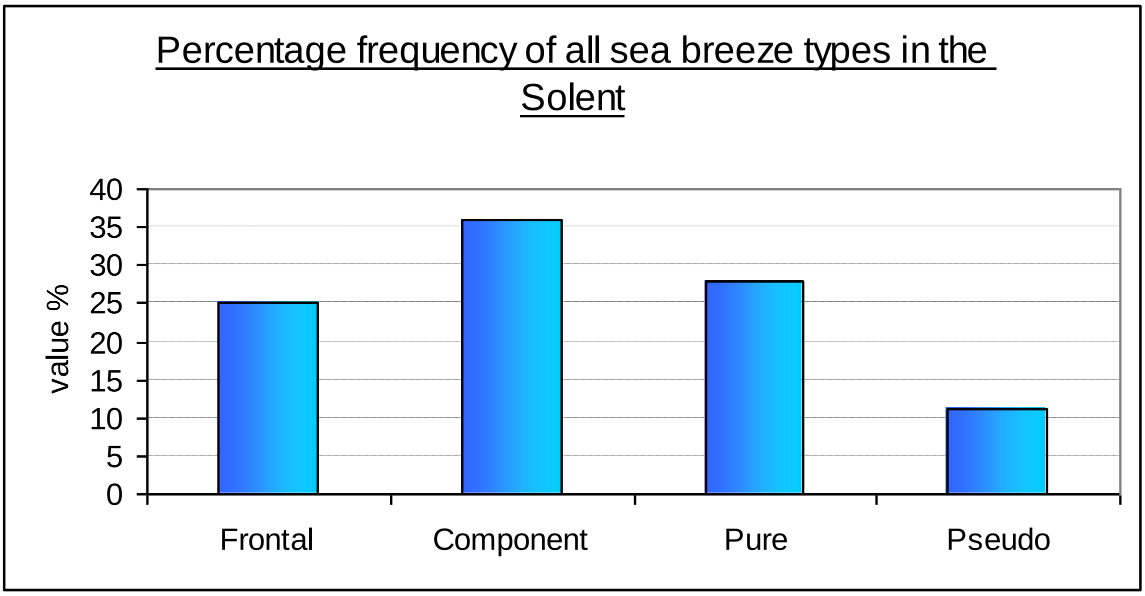


Figure 4.0. Percentage frequency of all sea breeze types in the Solent May – August 2006.

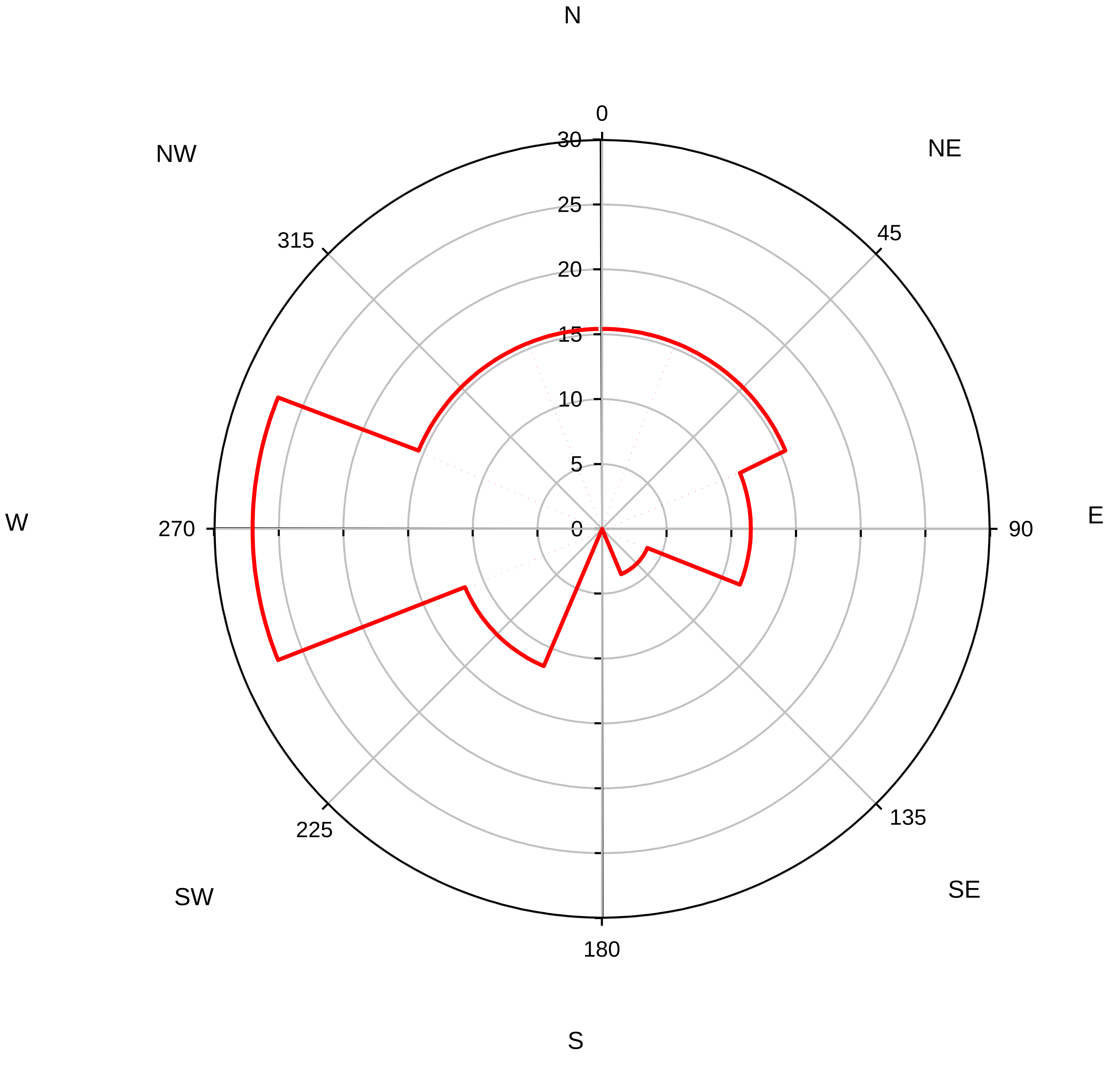


Figure 4.1. Percentage frequency of observed gradient wind directions before sea breeze onset.

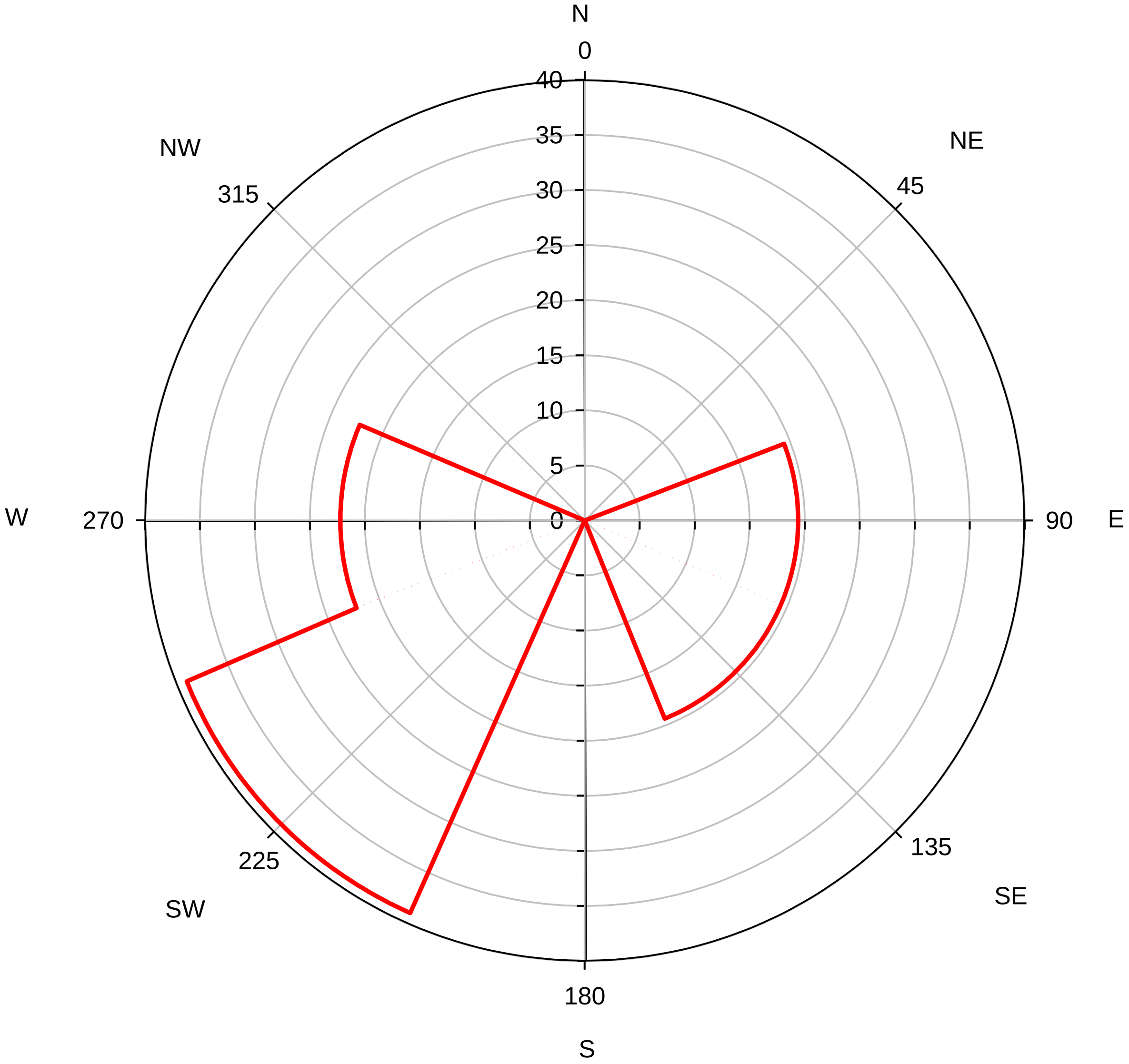


Figure 4.2. Percentage frequency of observed sea breeze directions.

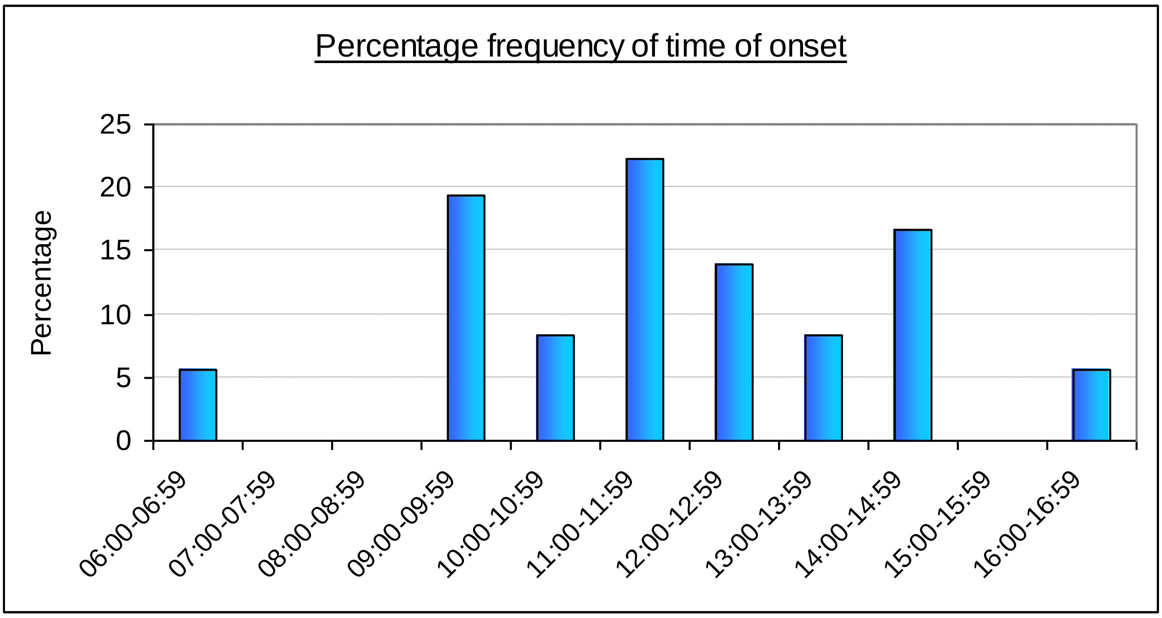


Figure 4.3. Percentage frequency of time of onset of sea breezes May – August 2006.

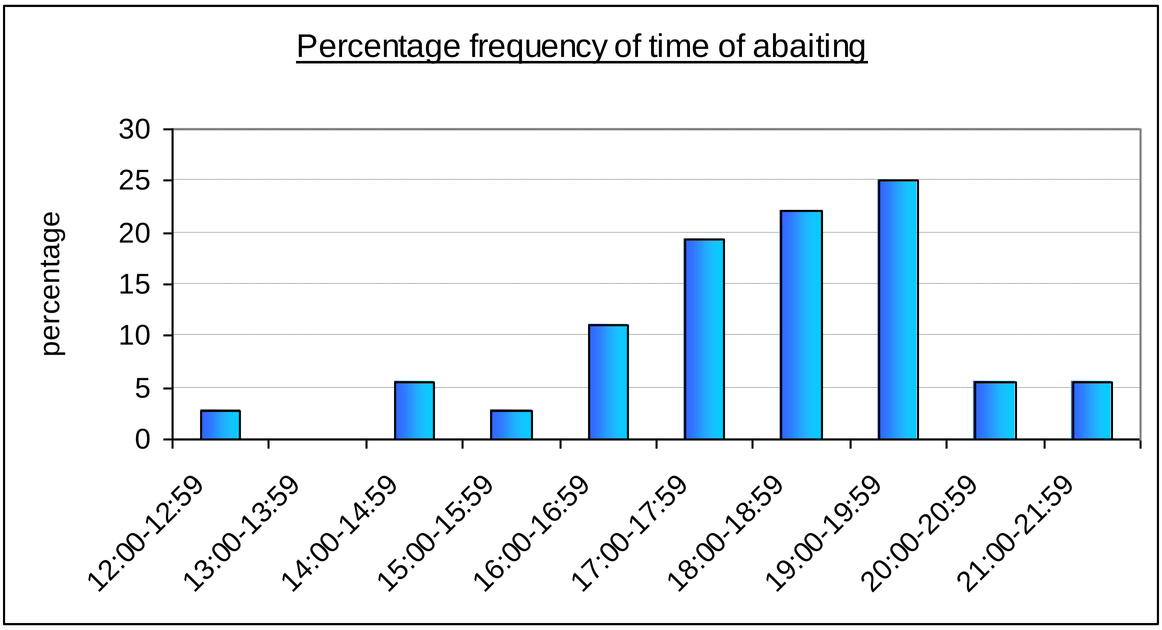


Figure 4.4. Percentage frequency of abatement time of sea breezes May – August 2006.

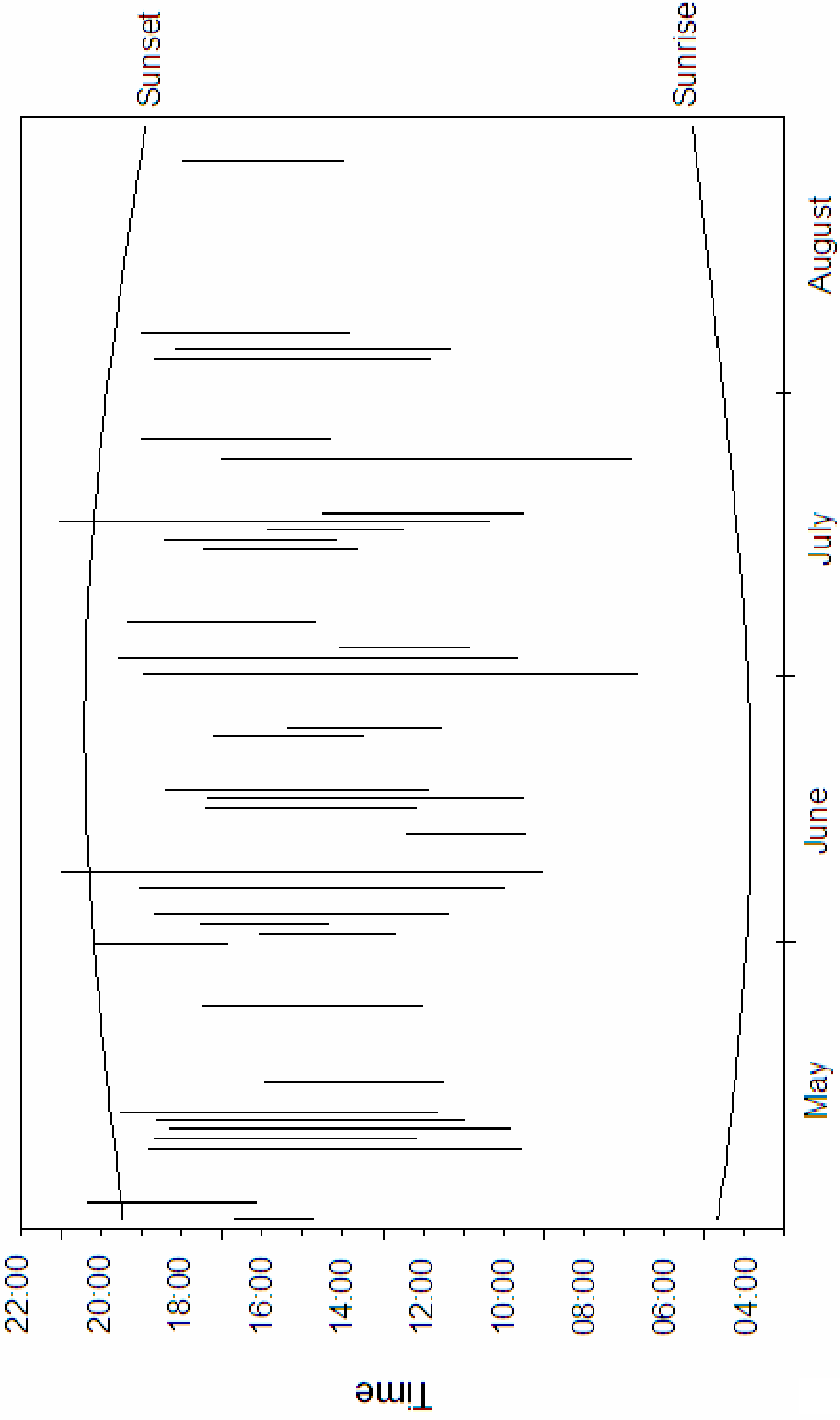


Figure 4.5. Duration of all observed sea breezes.

4.1. Case Studies
4.1.1. Frontal Event: 2nd June 2006

The synoptic situation for 00:00am 2nd June (figure 4.6) shows high pressure centred just off the SW tip of Ireland and the British Isles extending west into the Mid-Atlantic Ocean and east over NW Europe.

In the Solent at 08:00 the wind is from 346.73° at 3.67 knots dropping to 0.3 knots before the sea breeze onset. Air temperature was rising at ≈ 2.71°C.h^{-1} reaching 19.69°C before onset. Relative humidity was falling by 3.9%.h^{-1} and was 41.17 at onset. Observed visibility (diary) was poor and hazy possibly due to an inversion. Sea surface temperature was 14.11°C giving a maximum temperature difference before onset of 5.58°C. (See figures 4.7 & 4.8)

Onset was at 12:40, there was a sudden wind shift from 114.6° to 246.64°, Air temperature fell by 1.91°C in the first hour accompanied by an increase in relative humidity of 1.83%. Visible frontal characteristics were observed and formation of the sea breeze front and its advance inland to the top of Southampton Water is shown in figure 4.9. (1) shows clear skies over the south coast at 06:00 with cumulus clouds forming over the south downs by 09:00 with clearer skies inland (2), by 12:00 a distinct line of cumulus clouds parallel to the coast mark the SBF (3) with scattered cumulus clouds ahead of the front and clear skies seaward. The sea breeze is well established by 15:00 (4) with the SBF advancing slowly inland reaching the top of Southampton water and cumulus clouds ahead of the front burning off in the heat of the day. By 18:00 the air-sea temperature difference has dropped and the circulation dissipates itself (5).

During the event the temperature difference $\theta_T - \theta_S$ required to generate the land air – sea air density difference for the sea breeze to occur was 5.58°C, the maximum strength of the sea breeze was 11.17 knots at 15:20.

Pearce (1965) stated that the sea breeze front (SBF) moves inland at approximately half the surface wind speed associated with it, the Dockhead recording station is approximately 8.6km north of the station on the Bramble Bank, based on Pearce's statement it is possible to work out when the SBF will reach the Dockhead station and show as a rise in relative humidity on the hodograph.

Distance north: 8.6km
Strength of sea breeze: 8.8kts = 4.5ms^{-1}

Time of arrival = distance north between stations / (0.5 × sea breeze strength)
= 8600 / (0.5 × 4.5)
= 3822 seconds ≈ 1hour

This is confirmed on the hodograph (figure 4.8) which shows relative humidity starting to rise at 13:40.

The sea breeze continued to blow until 16:00 where it started to abate with the wind slowly dropping off and backing towards the south as the land air-sea air density difference could no longer maintain the circulation. No land breeze formed possibly due to the air and sea temperatures remaining relatively close throughout the evening.

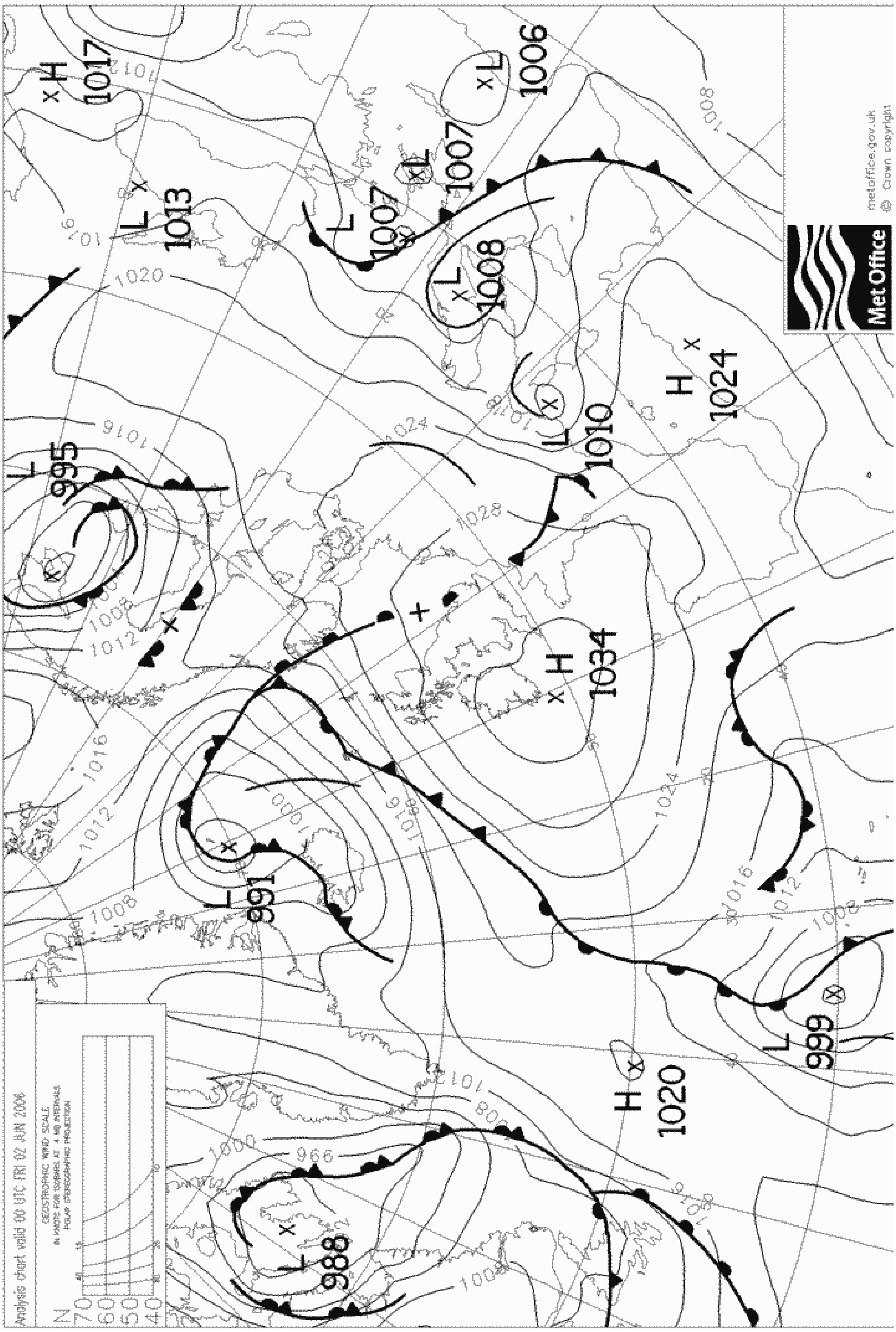
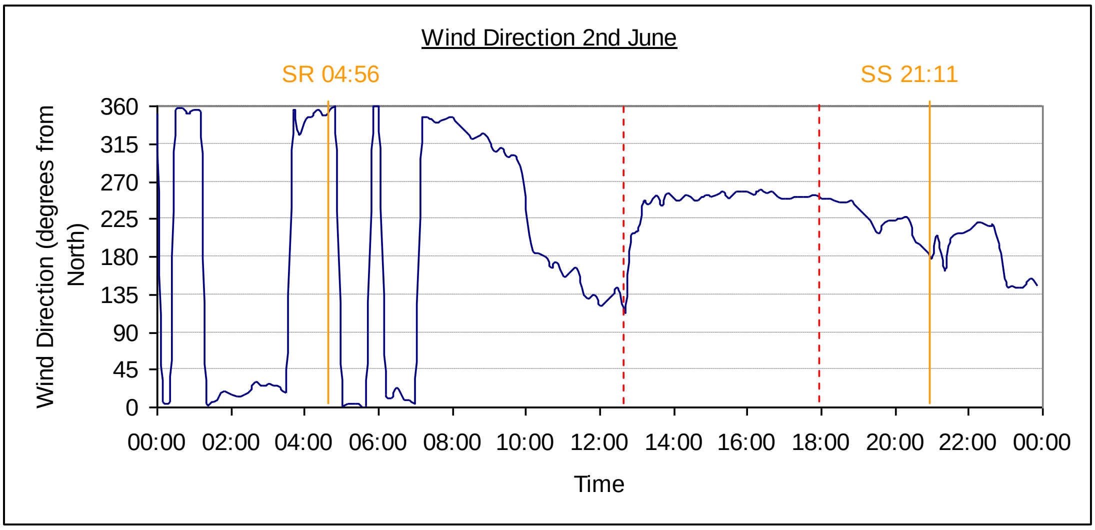
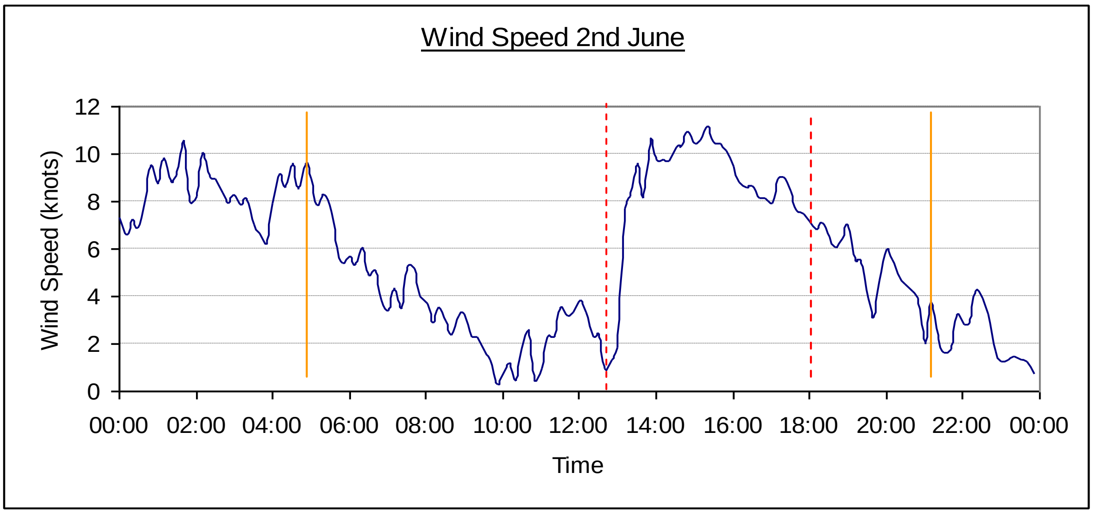


Figure 4.6. Synoptic Situation 02/06/06.





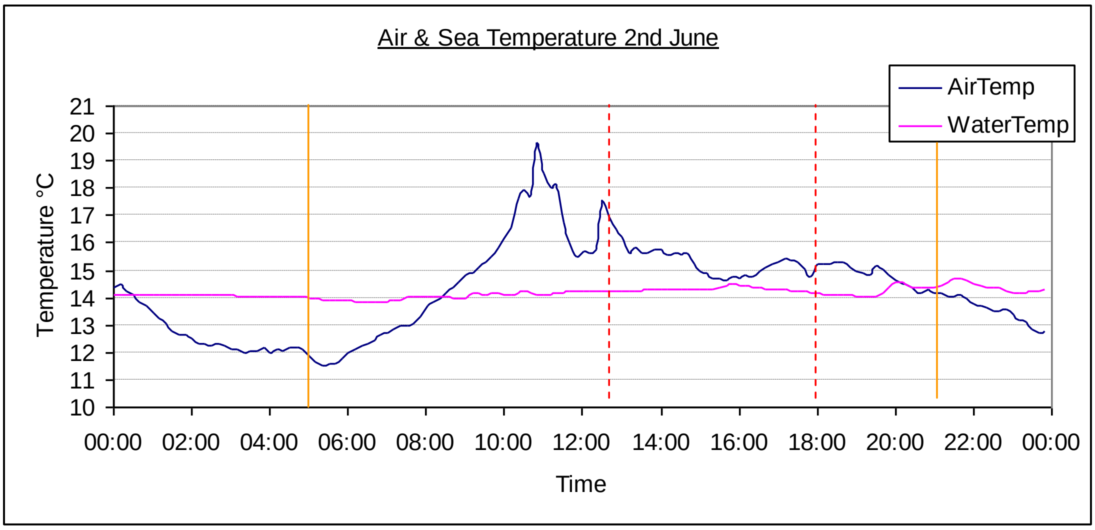


Figure 4.7. Wind and temperature field records from 02/06/06

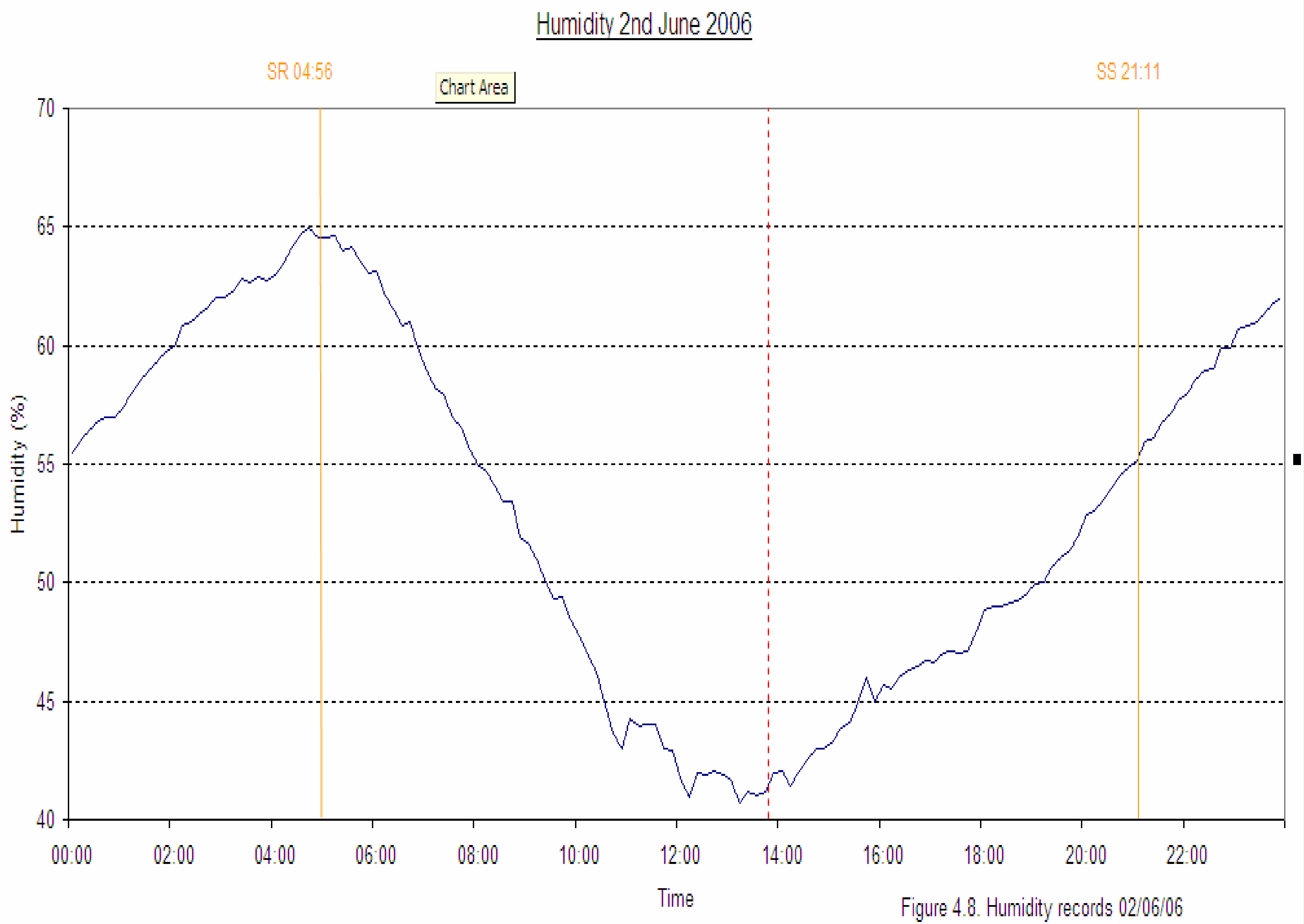


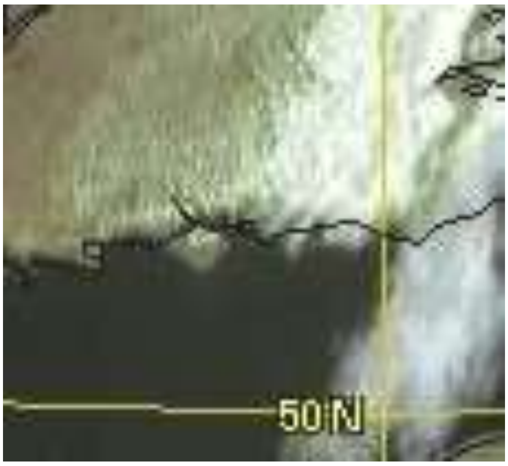
Figure 4.8. Humidity records 02/06/06

(1)

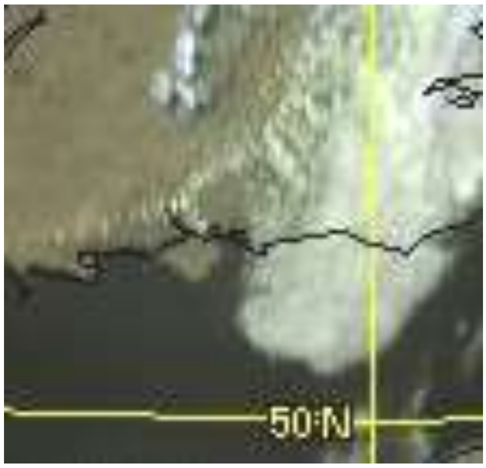

06:00 – 02/06/06

(2)

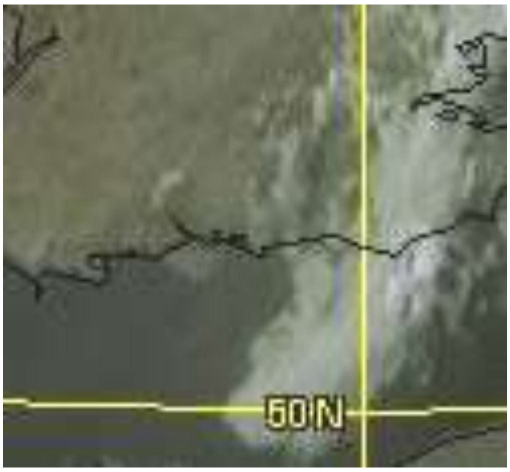

09:00 – 02/06/06

(3)


12:00 – 02/06/06

(4)


15:00 – 02/06/06

(5)


18:00 – 02/06/06

Figure 4.9. Satellite images showing formation of a sea breeze front and its advance inland 02/06/06

4.1.2. Easterly Component: 1st July 2006

The synoptic situation for 00:00 1st July (figure 4.10) shows an area of high pressure centred over Scandinavia extending SW over the British Isles where on the Atlantic coast three weak depressions are forming 1012mb, 1014mb and 1015mb respectively backed by a ridge of high pressure to the west. Continental Europe also has three areas of weak low pressure all 1017mb.

In the Solent the sea breeze started shortly after sunrise (04:56 BST) where the gradient wind was from 78.21° at 4.48 knots before dropping to 0.07 knots at 06:30 (figure 4.11). Air temperature was rising at ≈ 0.77°C.h^{-1} reaching 18.87°C before onset. Sea surface temperature was 18.44°C giving a maximum temperature difference at onset of just 0.41°C, the temperature difference increased throughout the day reaching a maximum of 3.2°C at 13:40.

The sea breeze became established at 06:40 with a wind shift from 65.17° to 105.94°, the air temperature fell by just 0.15°C at onset as the wind speed increased from 0 – 8 knots before settling at an average wind speed of 8.63 knots and maximum wind speed of 11.63 knots. The sea breeze lasted for 12 hours 20 minutes before the wind started to drop off at 19:00 reaching 0 knots at 19:50 roughly an hour before sunset at 20:45 BST.

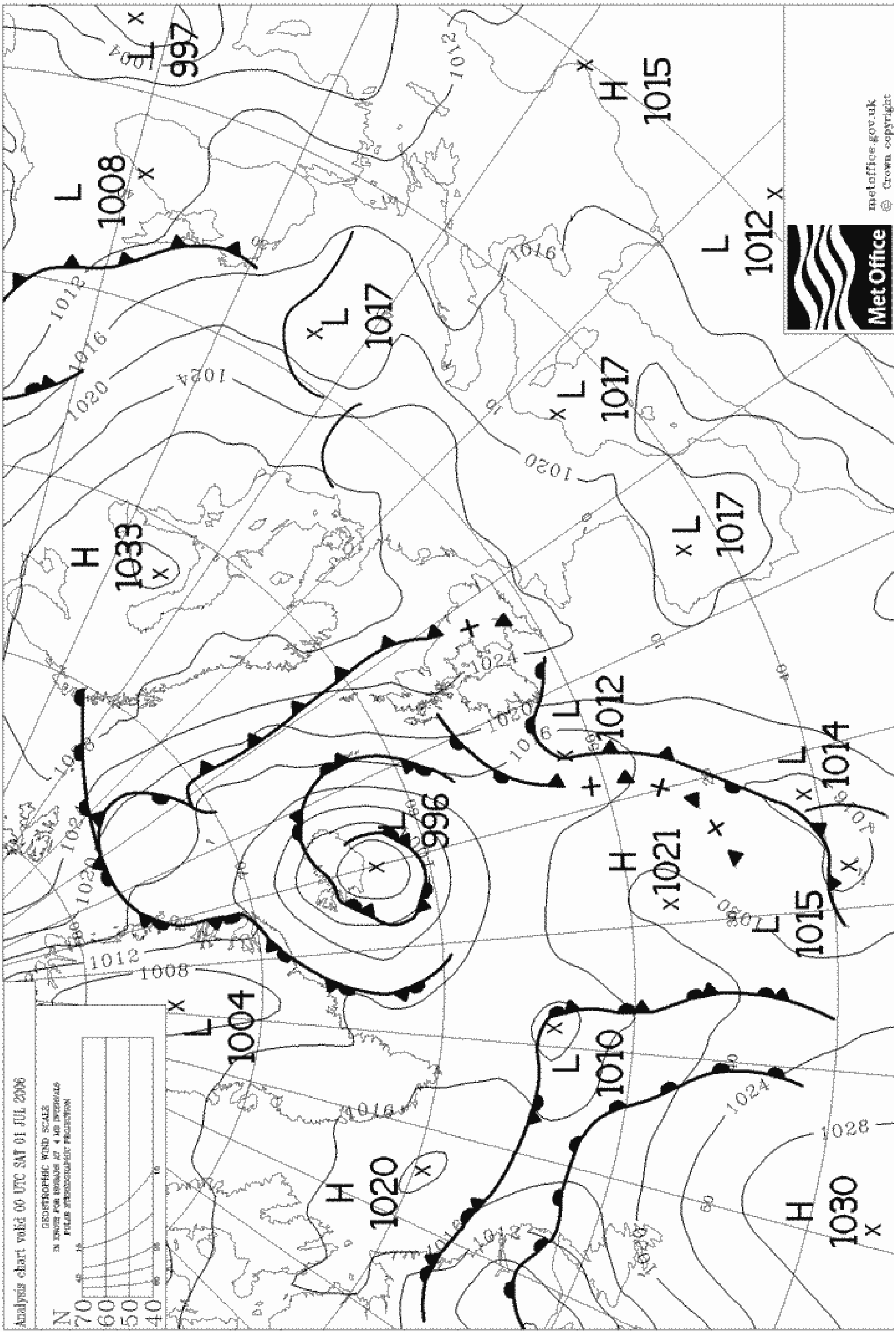


Figure 4.10. Synoptic Situation 01/07/06.

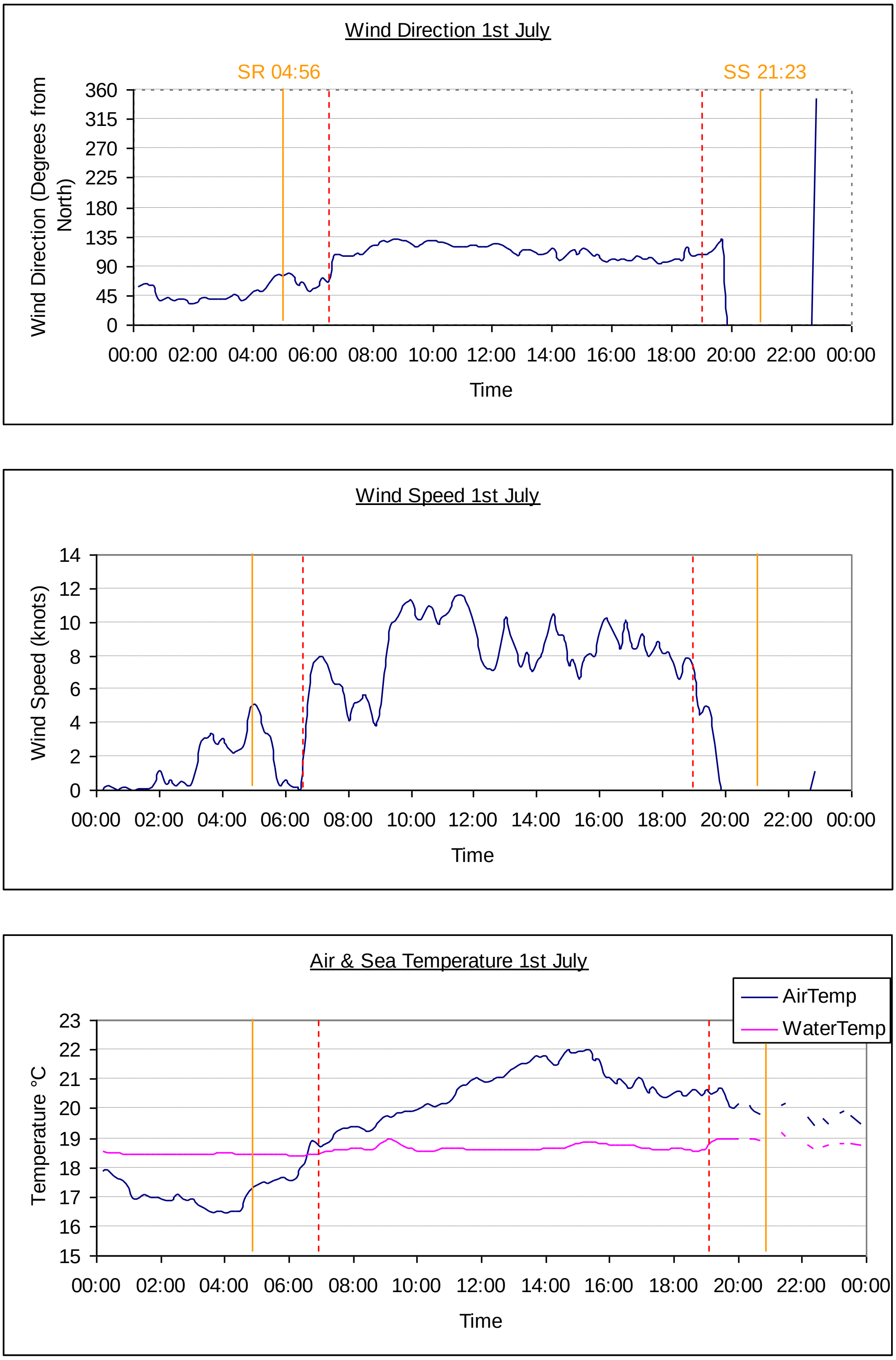


Figure 4.11. Wind and temperature field records from 01/07/06.

4.1.3. Westerly Component: 13th May 2006

The main influences on the synoptic situation on the 13th May (figure 4.12) are a depression (1004mb) over Sweden with a cold front extending SW over central England and into the Mid-Atlantic Ocean opposed by two areas of high pressure over continental Europe to the east.

Figure 4.13 shows at 09:00 the gradient wind was from 281.5° at 9.5 knots and air temperature was rising at ≈ $0.7°C.h^{-1}$ reaching a maximum of 15.4°C before onset giving the maximum temperature difference at onset as 1.9°C

The sea breeze onset at 11:40, 6 hours 21 minutes after sunrise, marked by a wind shift from 272.8° to 236.2° and a sharp decrease in temperature of 1.9°C in the first hour while wind speed increased gradually to an average speed of 16 knots, peaking at 20.1 knots at 16:30.

After blowing for 7 hours 50 minutes the sea breeze started to abate at 19:30, the wind veers from 237.8° to 280° and wind dropping off 12 knots within the hour accompanied by a sharp rise in temperature at the same time of 1.3°C.

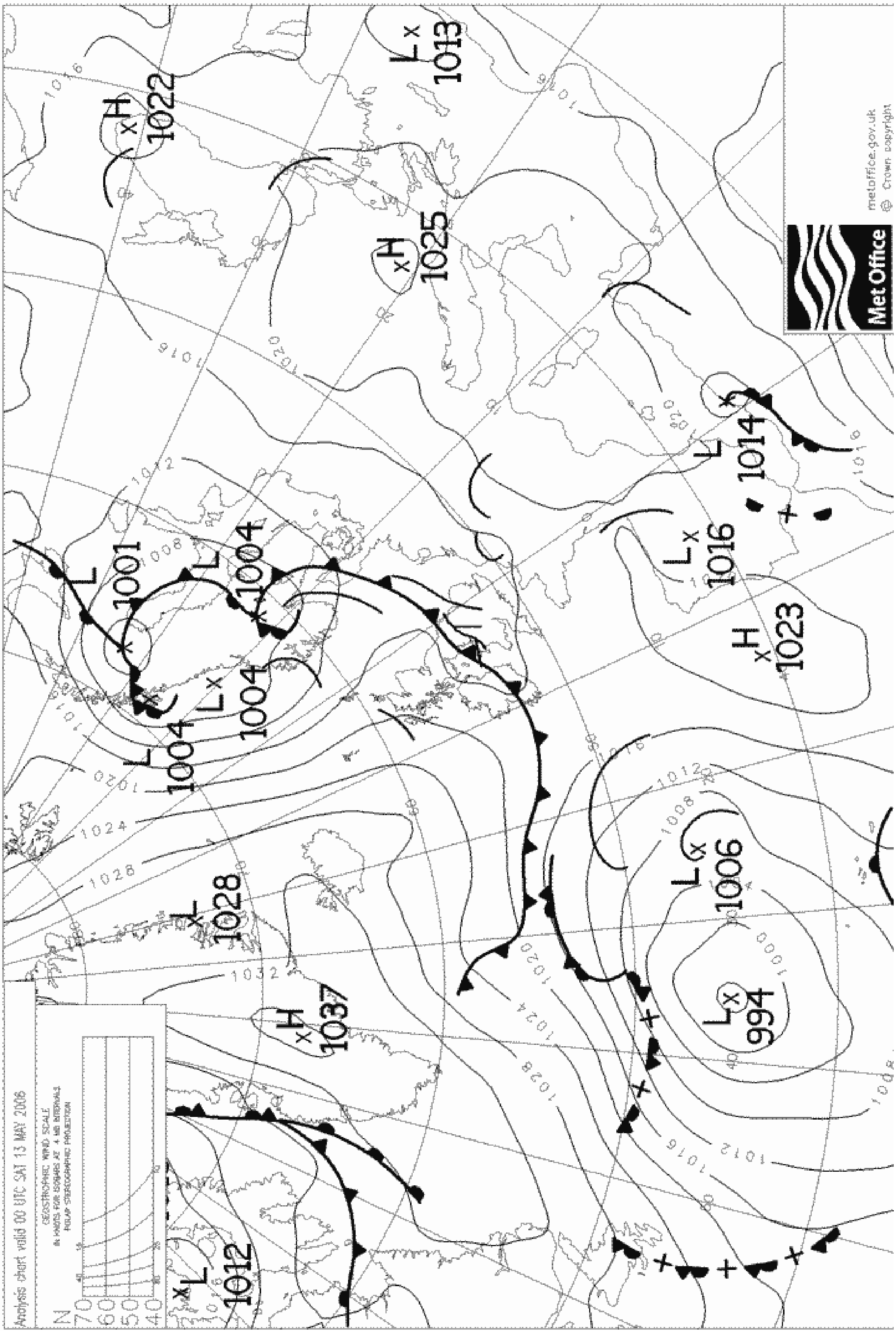
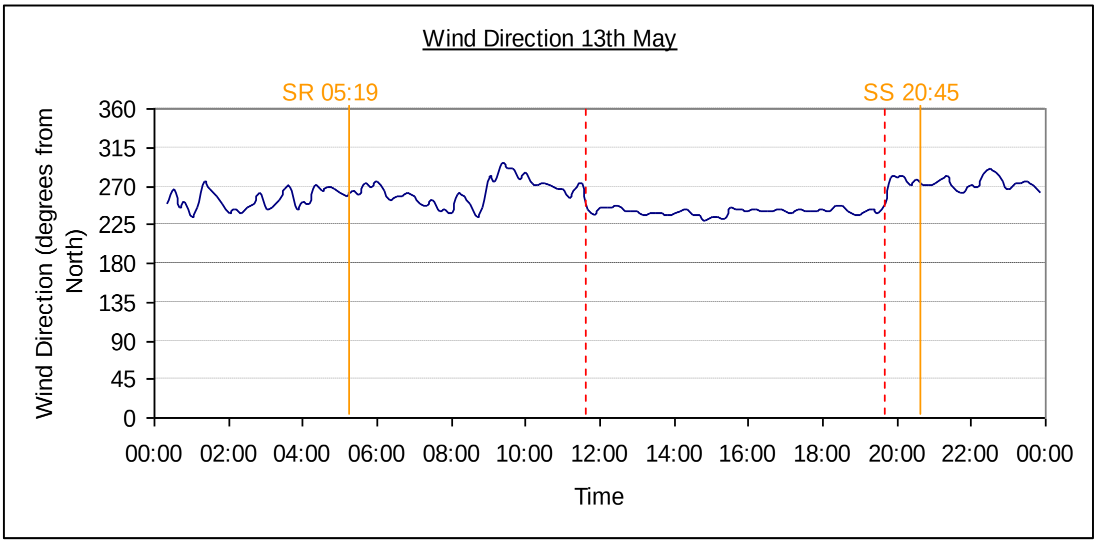
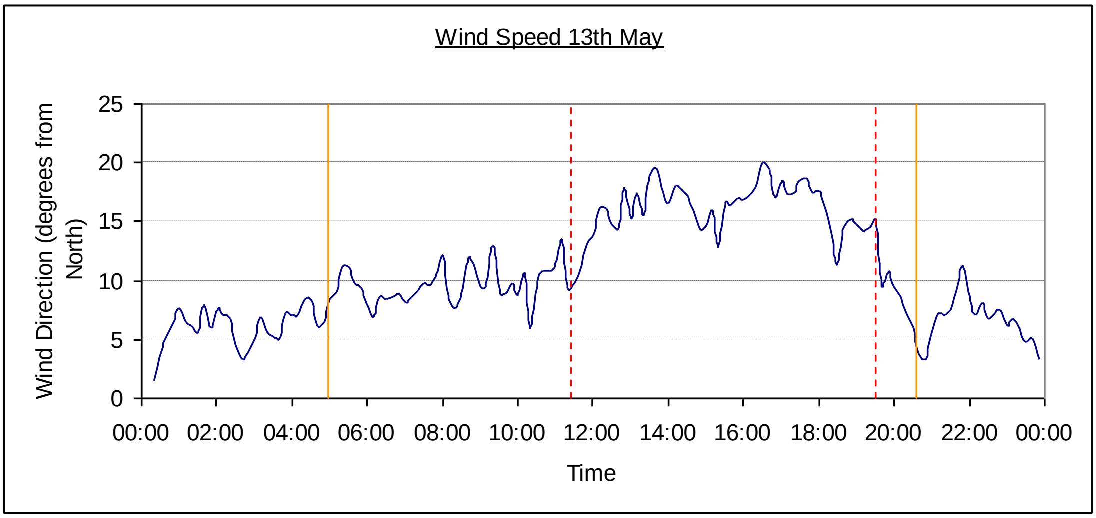


Figure 4.12. Synoptic situation 13/05/06.





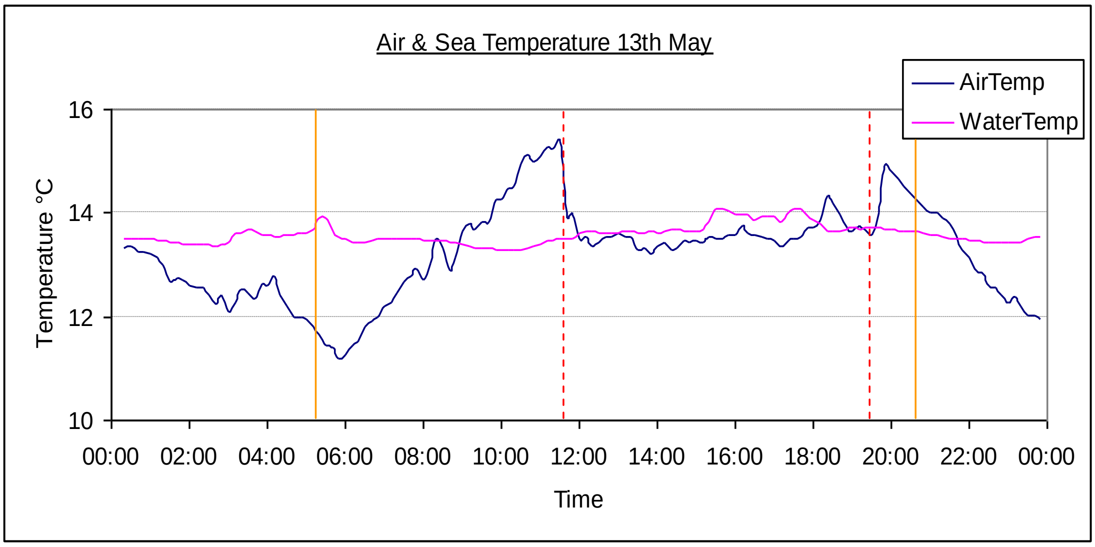


Figure 4.13 Wind and temperature field records from 13/05/06

4.1.4. Pure Sea Breeze: 17th June 2006

The synoptic situation 17th June (figure 4.14) shows an anticyclonic ridge (1021mb) extending over central and southern England.

Figure 4.15 shows that from sunrise (04:51) the wind is light and variable swinging between 0° and 168.1° with gusts reaching 2.46 knots. Air temperature was rising at 1.56°C.h^{-1} reaching a maximum of 19.34°C before onset. The sea surface temperature was 17.64°C giving a maximum air – sea temperature difference at onset of 1.7°C.

Onset was at 09:30 with the wind veering from 0° to 242.4° and gusting up to 10.1 knots reaching a maximum of 11.77 knots at 10:50. Fluctuations in the movement of the sea breeze cause resultant fluctuations in air temperature as seen in the thermograph in figure 3.9, at 10:45 the air temperature dropped to 18.45°C reducing the air – sea temperature difference to just 0.75°C, with this small difference in temperature the sea breeze struggled to maintain a strong enough land air – sea air density difference and the circulation weakened, dropping off to 0.18 knots at 12:10 before the air temperature rose to 20.3° immediately after restoring the density difference and the sea breeze circulation.

The sea breeze abated at 17:30 with the wind speed dropping from 8 knots to 2.69 knots and air temperature rose by 0.86°C.

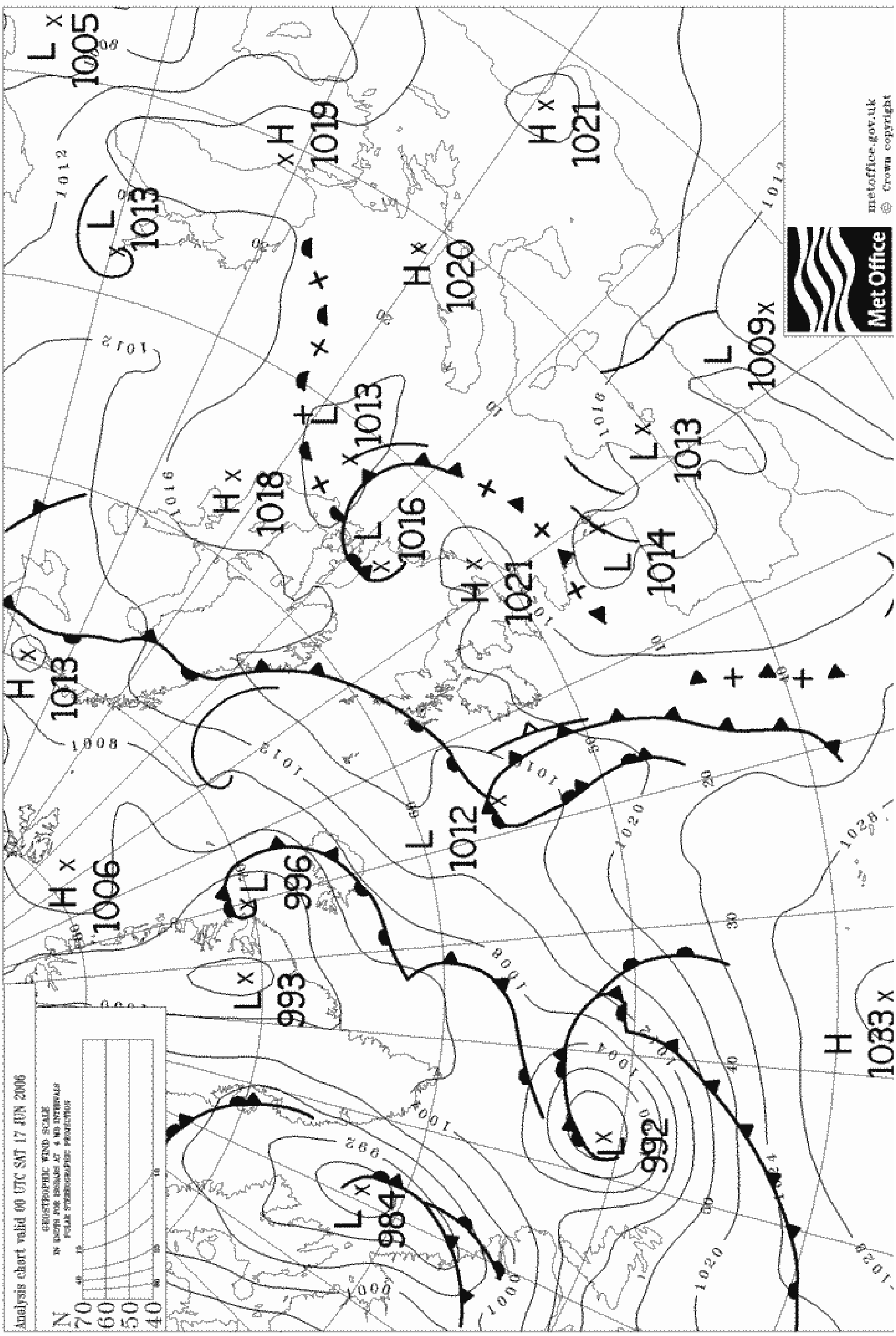
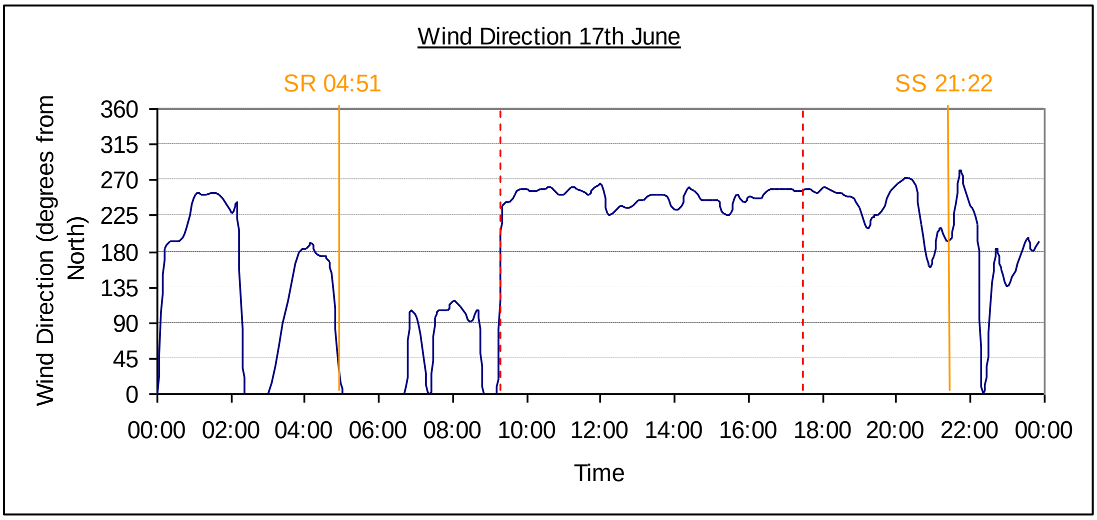
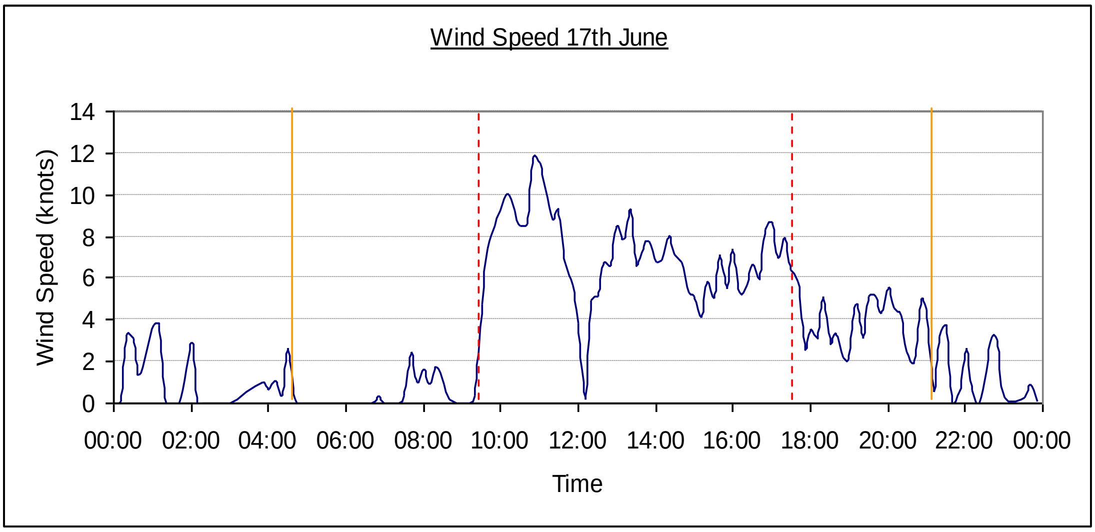


Figure 4.14. Synoptic situation 17/06/06.





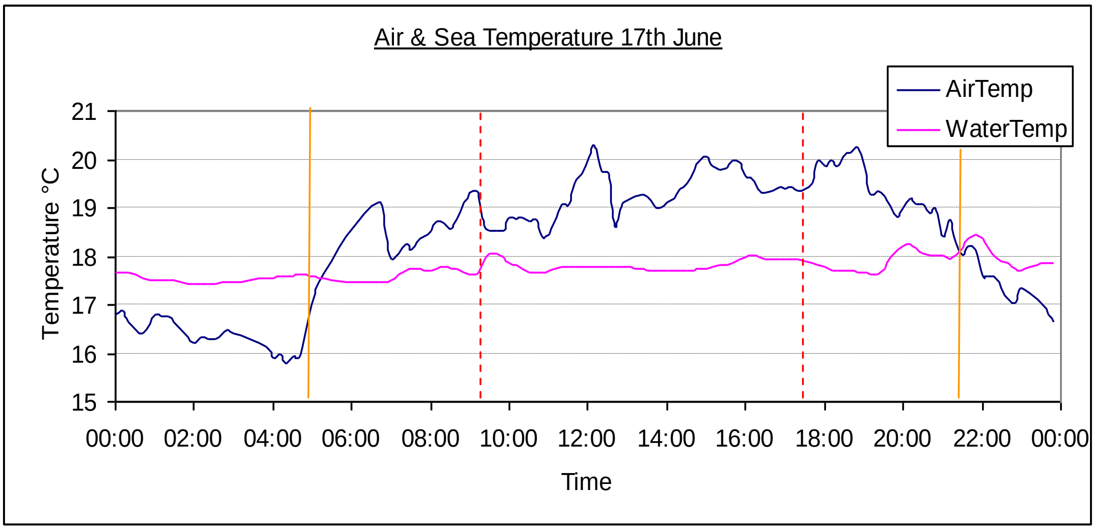


Figure 4.15. Wind and temperature field records from 17/06/06

4.1.5. Pseudo Sea Breeze: 16^{th} June 2006

The synoptic situation for 00:00 16^{th} June (figure 4.16) is dominated by a ridge of high pressure (1025mb) extending north-eastwards from the Atlantic and over central and southern England.

Figure 4.17 shows at 09:00 the gradient wind was from 247.3° at 0.2 knots and air temperature was rising at 0.77°C.h^{-1} to a maximum of 19.28°C before onset. Fluctuations in wind direction and speed mark the sea breeze component before it onsets at 12:10 with the wind returning to 252° (a wind field change of ≈ 5°) and a gust of 5.43 knots marking the arrival of the sea breeze, the wind continued to gradually increase to a maximum of 12.93 knots at 16:20 before abating at 17:30 as the land air-sea air density difference reduced and could no longer enhance the strength of the gradient wind.

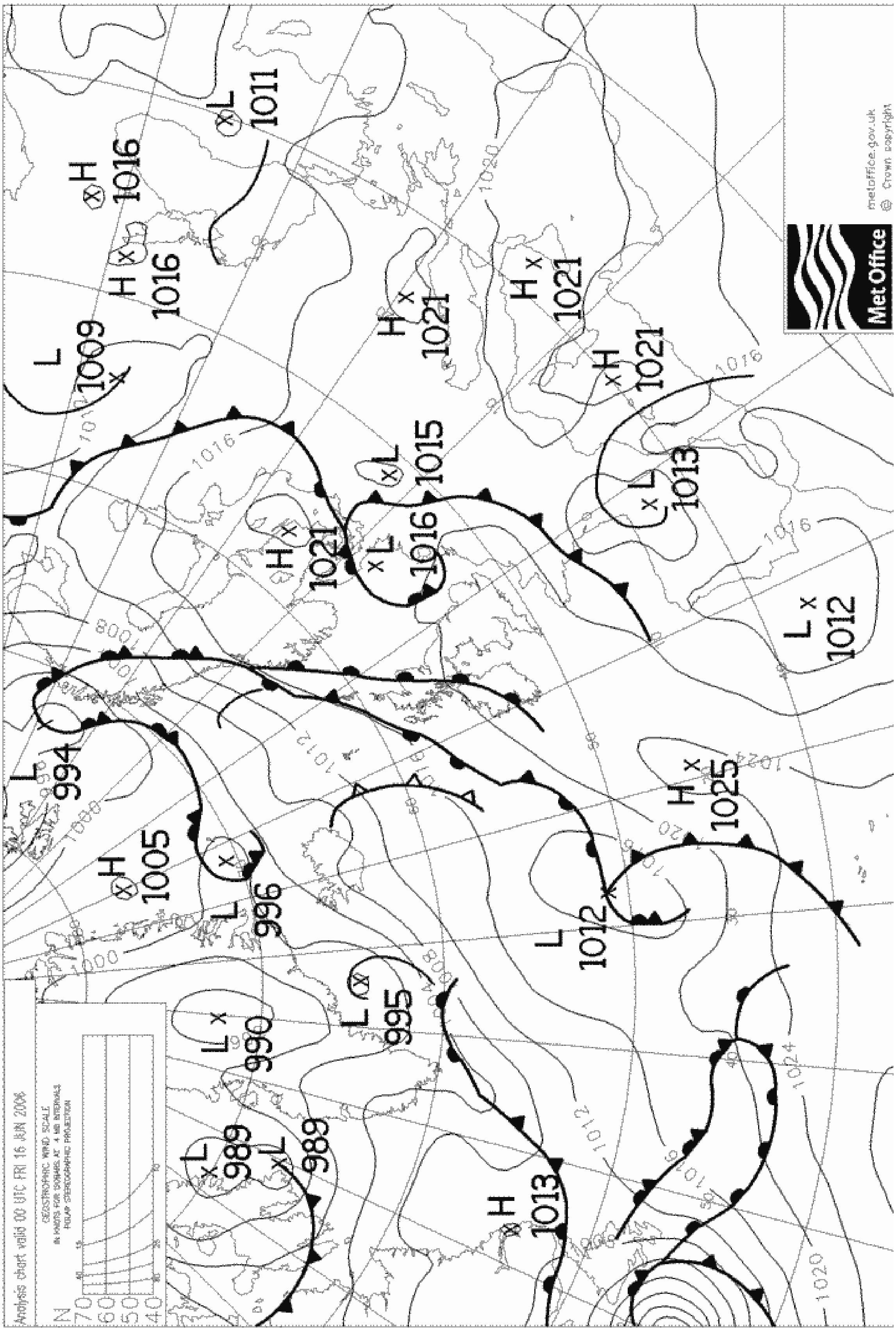
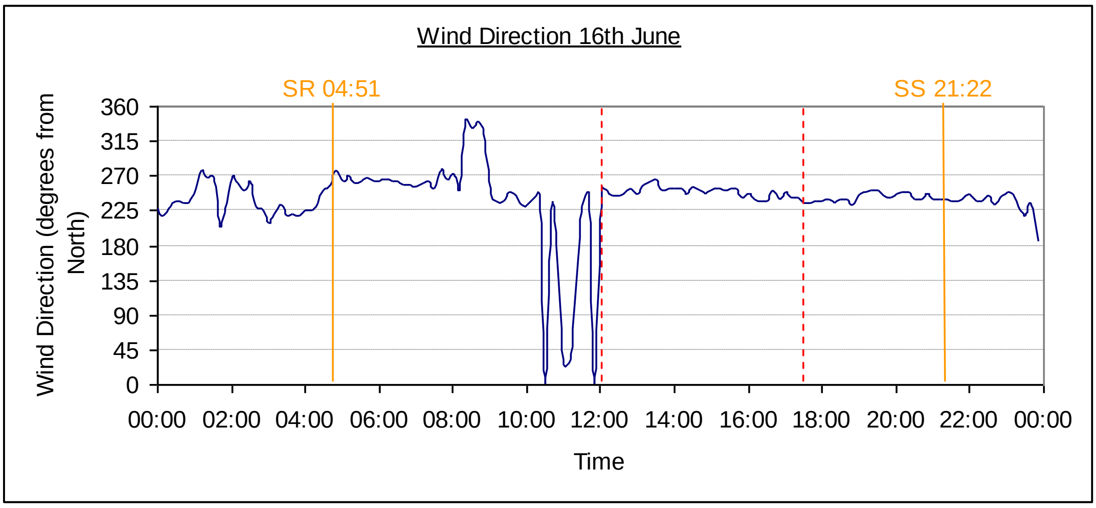
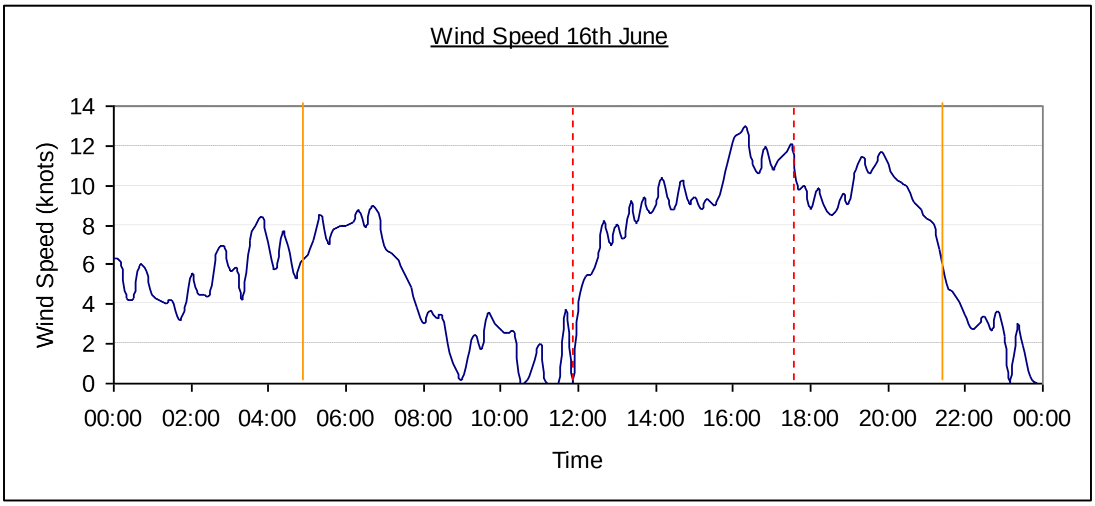


Figure 4.16. Synoptic situation 16/06/06.





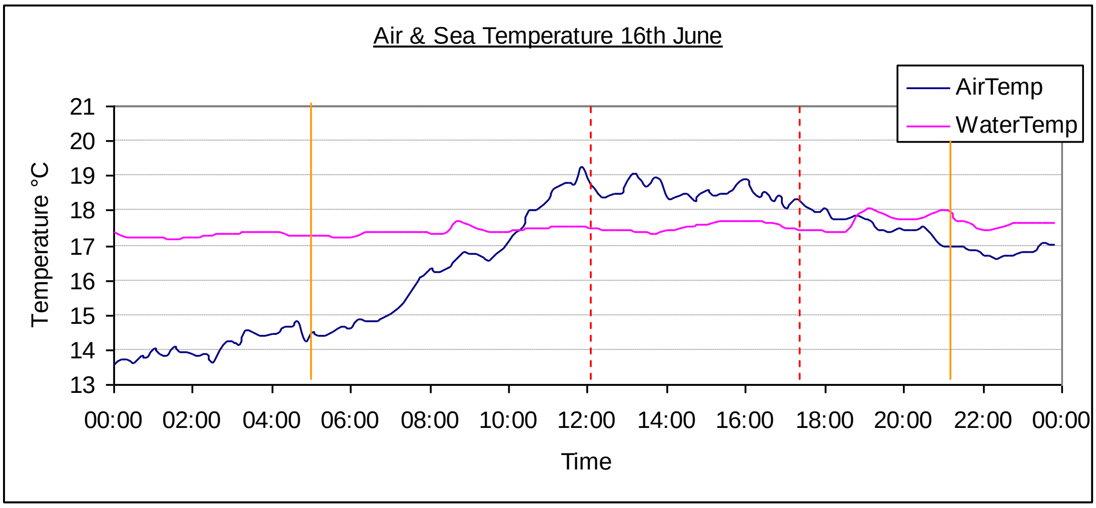


Figure 4.17. Wind and temperature field records from 16/06/06

4.1.6. Watts' Forecast Model

All days with an offshore gradient wind were put into an adapted version of watts (1955) forecast model for Thorney Island, there were 21 occurrences where the sea breeze occurred under these conditions. The re orientated model for Calshot predicted the time of onset of 57% of the sea breeze occurrences to with in one hour and 71% within one hour and a half. Results are shown in Table 3.1 below.

Offshore gradient wind days	Geostrophic windspeed before onset (kts)	Surface Wind direction	Predicted time of onset (Watts)	Actual Time of onset	Time Difference
01.05.06	8.5	262.3	10:20	14:40	04:20
03.05.06	13	228.4	13:15	16:10	02:55
09.05.06	13	273.5	14:00	09:30	04:30
10.05.06	10	332.6	11:20	12:10	00:50
11.05.06	7	72.3	10:50	09:50	01:00
12.05.06	3	16.1	09:20	08:20	01:00
13.05.06	10	259.7	11:00	11:40	00:40
16.05.06	12	211.6	12:20	11:40	00:40
25.05.06	9.5	235.4	10:40	12:00	01:20
01.06.06	11	319.04	13:00	16:50	03:50
02.06.06	7	13.87	11:15	12:40	01:25
03.06.06	11	307.44	13:20	14:20	01:00
07.06.06	5	275.19	09:30	10:00	00:30
13.06.06	6	315.82	10:00	09:30	00:30
16.06.06	9	253.44	10:40	12:10	01:30
03.07.06	10	340.14	11:30	09:30	02:00
11.07.06	13	279.15	14:40	14:40	00:00
25.07.06	4	38.16	09:40	06:50	02:50
05.08.06	8	349	11:00	11:50	00:50
08.08.06	12	48.98	15:00	14:00	01:00
27.08.06	14	268.98	14:30	14:00	00:30

Table 3.1. Results from Watts forecast model.

5.0. Discussion

5.1. The Air-Sea Temperature Difference.

The air-sea temperature difference required to establish each type of sea breeze seems to be related to the amount of work (energy expended) the sea breeze component has to do to establish itself. The average air-sea temperature differences required to generate each type of sea breeze are summarised below in Table 4.0.

Sea Breeze Type	Average Air-sea Temperature difference required.
FRONTAL	4.9°C
PURE	3.8°C
COMPONENT	2.7°C
PSEUDO	2.7°C

Table 4.0. Average air-sea temperature differences required to produce each type of sea breeze in the Solent.

A frontal sea breeze must overcome the offshore gradient wind before the sea breeze onsets a greater θ_A-θ_S (4.9°C) is required to raise the air temperature over the land enough so that the sea breeze circulation can start as in figure 2.0. It has been established that the sea breeze will not form if the offshore gradient wind exceeds $8ms^{-1}$, up until this point however θ_A-θ_S must increase with increasing wind speed if the sea breeze is to onset at the same time. (Brittain, 1966)

Hope-Hislop, (1974) suggests that a temperature difference of 2-4°C is adequate to form a pure sea breeze, the average value of 3.8°C obtained in the Solent agrees with this statement. To form, the pure sea breeze requires the second highest temperature difference, with initially zero or very little (<1 knot) gradient wind the temperature difference must establish a strong enough density gradient to cause movement in an initially static atmosphere.

With the gradient wind already blowing from an onshore or alongshore direction both component and pseudo sea breezes have far less work to do in aligning the sea breeze perpendicular to the coastline and both only require a temperature difference of 2.7°C.

The magnitude of the temperature difference didn't have a bearing on the time of onset of the sea breeze.

5.2. Effects of Gradient Wind

For frontal events there seemed to be some correlation between the strength of the offshore wind and the time that the sea breeze onset. Stronger winds tended to delay onset with weaker winds encouraging earlier sea breeze development, the mid-strength winds encompassed a wider spread of the onset times. Figure 5.0 shows the gradient wind at the surface plotted against time of onset of the sea breeze, there are 3 clear divisions: when the wind speed is below 4 knots the sea breeze onsets before 11:00. If the wind is 4-7 knots the sea breeze develops 11:00-15:00, and when the offshore wind speed is above 7 knots onset of the sea breeze is delayed until after 16:00.

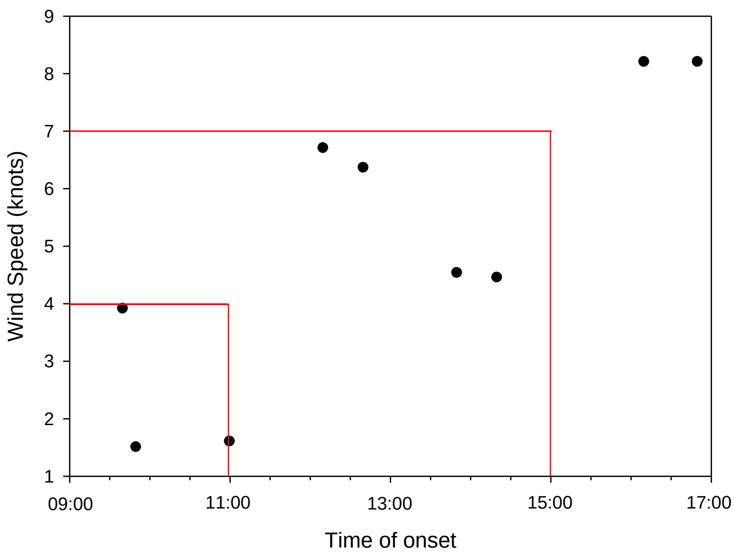
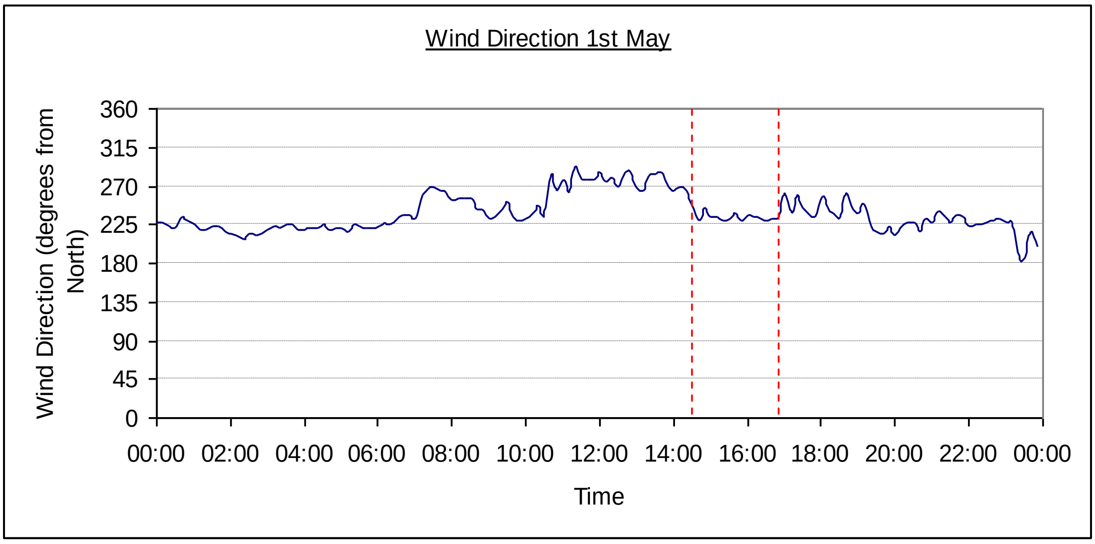
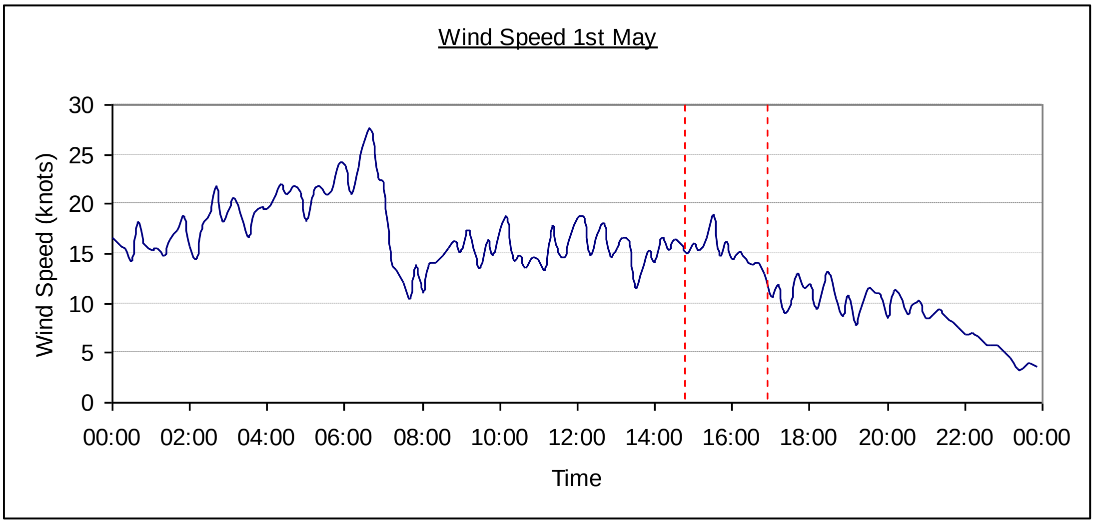


Figure 5.0. Gradient wind at surface against time of onset for frontal sea breezes.

On the formation of pure sea breezes Pearce, (1955) states that there are very few occasions when the atmosphere is sufficiently calm for the sea breeze to be the only disturbance, for this reason calm conditions are assumed when the gradient wind is < 1 knot. Just a small movement of air causes frictional forces in the boundary layer to disturb or hinder sea breeze development (Anthes, 1978). Assuming the atmosphere is calm and a sufficient air-sea temperature difference exists, further atmospheric obstacles may still restrict sea breeze development. A low level temperature inversion, which develops better in calm conditions was observed on 24.06.06 visible over the eastern side of the Solent and Cowes on the Isle of Wight with reduced visibility in hazy conditions due to photogramatic smog at low level and clear blue skies above. The presence of this inversion meant water vapour in the convecting air attached to particles in the air column and started to form a layer of low cloud at the inversion boundary that reduced the amount of solar radiation reaching the surface, weakening the driving mechanism and delaying the sea breeze onset until 13:30 whereupon most of the cloud had burned off. Also this burning off of mist and cloud by evaporation costs a lot of solar energy and prevents the air temperature from rising as it would have done in the absence of cloud and mist droplets.

Onshore gradient winds carry cool and moist sea air in over the land, which has the effect of dampening solar heating and convection; this has a more pronounced effect as the wind speed increases. Faster winds dissipate heated air at the surface more quickly; a higher rate of heating is then required to establish a sea breeze. Often this effect causes delayed onset of the sea breeze as observed 01.05.06 (figure 5.1), before onset the wind was 15.1 knots only increasing to 15.3 knots and backing through 28.2° to a SW direction at 14:40, the sea breeze was short lived and abated at 16:50





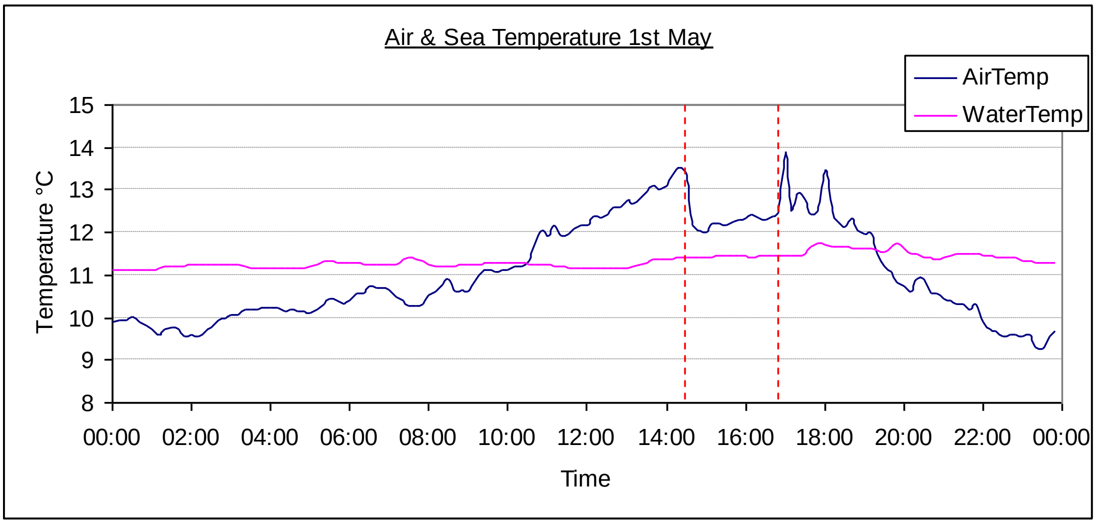


Figure 5.1. Wind and temperature field records from 01/05/06.

5.3. Evaluation of Watts' Forecast Model

Sea breezes are widely documented to extend up to 200km horizontally; Thorney Island is 30km from Calshot in an easterly direction, well within quoted figures for horizontal extent. If this is true the prediction curves from Watts (1955) will need no or very little alteration just having to shift each offshore wind sector to suit Calshot's orientation, unlike similar studies conducted by Brittain (1966), Pepperdine (1966) who reproduced the forecasting curves, adapting the model to the Lincolnshire coast with a similar degree of success to Watts.

When applied to actual sea breeze events at Calshot the reoriented model was 57% accurate (compared with Watts 69%) in predicting time of onset within an hour with 75% of occurrences predicted within an hour and a half of actual occurrence.

Wind speeds input into the model were obtained using estimates of geostrophic wind taken from synoptic charts, used in conjunction with direction at the surface; this may have been improved upon by use of pilot balloon ascents to obtain actual data, however this becomes expensive and was not possible for this study.

Watts took observations at Thorney Island for 3 years (1951-54), effectively 3 sea breeze seasons, compared to this study which uses one season. The longer data collection period will have undoubtedly had a bearing on the accuracy of Watts' model; however in applying the model to Calshot a value of 57% accuracy suggests that the model may be applied here successfully and that the two locations share many of the localised effects common to the sea breeze in the Solent.

The difference of 12% between Thorney Island and Calshot may be attributed to a number of factors; the period of data collection as already discussed and localised effects from channelling down the western Solent dying off by Thorney Island as documented by Watts, (1987)

5.4. Effects of Tidal mud/sand flats

Watts (1955) proposed that the presence of large areas of sand or mudflats that become exposed to the air at low tide can have a significant effect upon the difference between inshore and mid-channel sea surface temperatures either heating on a summers day as water flows over mud heated by the sun or conversely cooling in the winter as water comes in contact with mud previously exposed to nocturnal radiation, this effect is quite marked in the Solent and can be seen in figure 5.2. In the Solent this more pronounced cooling in the winter and heating in the summer may alter the months during which the mechanism by which sea breezes form is present. The Solent is 3.31°C cooler than mid-channel temperature in January, this increases the likelihood of sea breeze occurrence earlier in the year, however the Solent reached 20.1°C in August (2°C warmer than mid-channel) meaning higher air temperatures must be sustained for sea breezes to occur, this explains why only four sea breezes were observed in August and may be observed in figure 5.3 showing the daily maximum air temperature in the Solent during 2006 against the mean monthly sea surface temperature

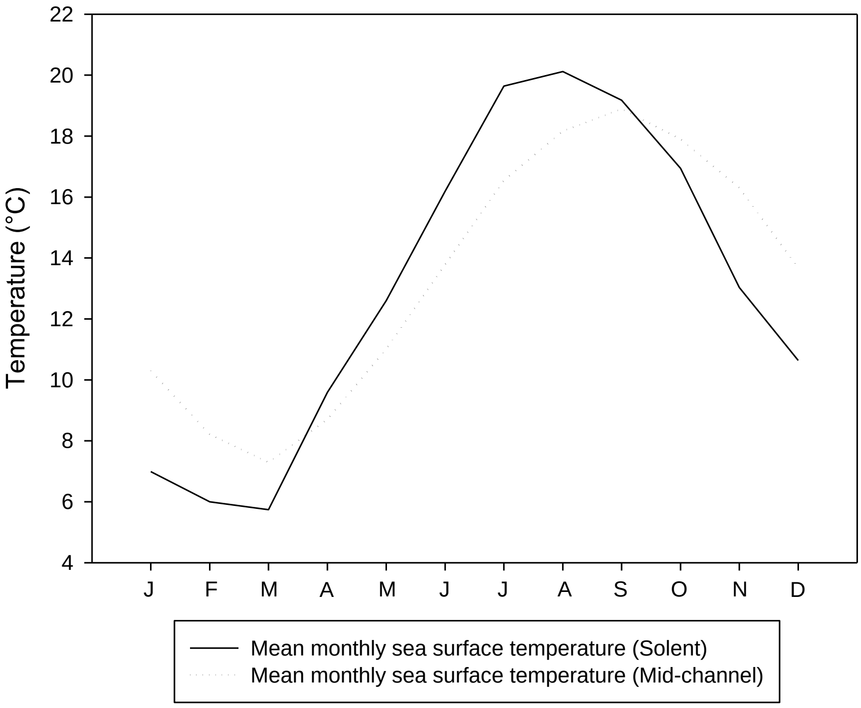


Figure 5.2. Comparison of mean monthly sea surface temperature in the Solent and Mid-channel (Greenwich Lightship) 2006.

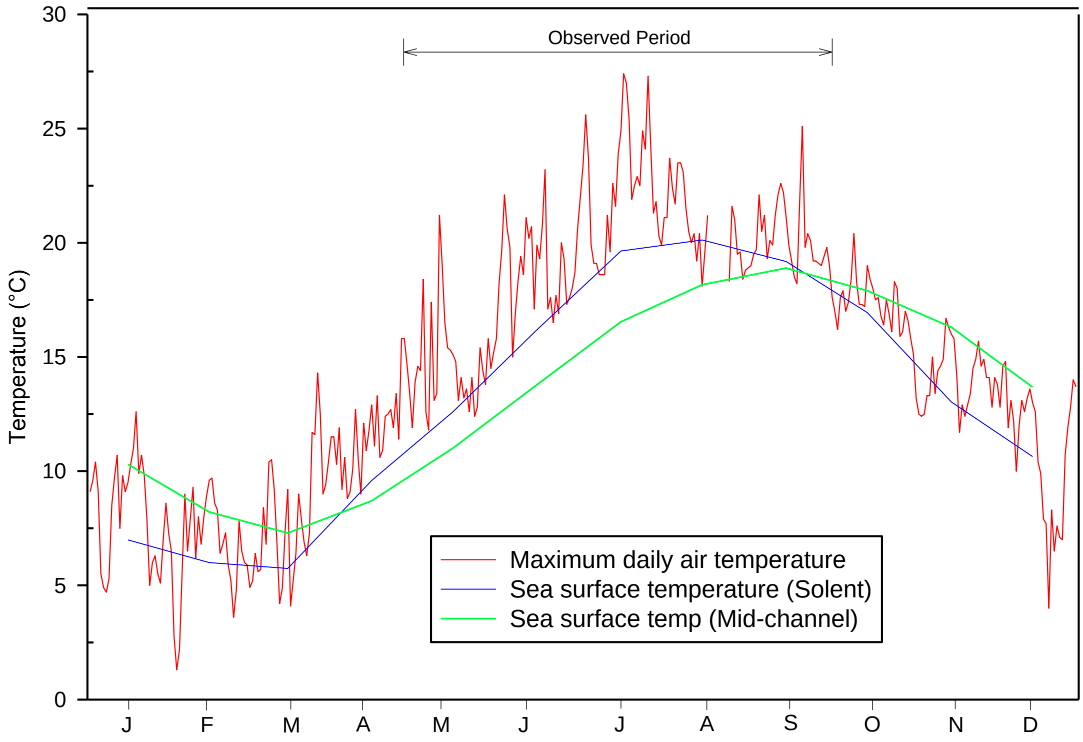


Figure 5.3. Air and Sea temperatures in the Solent 2006

The presence of mud flats in the Solent reinforced the formation of a sea breeze 12th May; low tide was at 04:43 at a height of 0.9m (springs) exposing the sand and mudflats at a time where the air temperature is the coolest, reaching a low of 11.9°C and also before any solar heating had started to take place (sunrise: 05:21), as a result the sea surface temperature dropped 0.5°C (from 13.6°C to 13.1°C) increasing the air-sea temperature difference to 2.7°C before the sea breeze onset at 11:00 coinciding with high tide (11:03, 4.2m).

This shows that sea breezes can occur on many days when, if mid-channel temperatures were used the possibility of a sea breeze would be ruled out.

5.5. Effects of Topography

With observed results clearly showing that the sea breeze follows one of two routes of approach in the Solent (see fig 2.3) it confirms the statement made by Watts (1987) "the Solent sea breeze has a double effect." No sea breezes were observed from a southerly direction suggesting that the high ground extending from the southern tip of the Isle of Wight to the Needles forms a formidable barrier for the sea breeze to overcome causing it to deflect and flow up either the east or west channel of the Solent, it also implies with land reaching heights up to 300m the Solent sea breeze circulation is unlikely to extend much higher than this itself in agreement with previous work done by Peters, (1938); McPherson, (1970); Kikuchi *et al*, (1981) and Theodoros *et al*, (2005).

5.6. Coriolis Deflection

As wind speed and the size of the fetch increases, the Coriolis force has a more pronounced effect; initially the sea breeze blows normal to the density gradient (parallel to the coast) that produces it, (Fisher, 1960). As described earlier the Coriolis force may be observed by an added veering component in the sea breeze. The Coriolis Effect may be quantified by:

$$\frac{du}{dt} = 2 \, . \, \omega \, . \, v \, . \, \sin \text{latitude}$$

where ω = the earths angular velocity ($rad.s^{-1}$)

v = speed of flow ($m.s^{-1}$)

From Hope-Hislop, (1974)

By integrating this, the added veering component (in the northern hemisphere) of velocity perpendicular to the direction of flow may be evaluated for varying fetch distances (S) from the recording station on bramble bank shown in Table 4.1 (Derry, 1996).

$$u = \int 2 \cdot \omega \cdot v \cdot \sin \text{latitude} \cdot dt$$

$$u = 2 \cdot \omega \cdot S \cdot \sin \text{latitude}$$

S (km)	u (ms^{-1})
5	0.56
10	1.12
15	1.68
20	2.23
25	2.79
30	3.34

Table 4.1. Quantification of added veering component with increasing fetch

Sea breezes flowing up the western Solent have a smaller fetch (20.5km) giving them an added veering component of (2.23 knots) but due to already having a westerly component require less input from the Coriolis force to cause the wind to align parallel with the coast The average flow speed of sea breezes flowing up the west Solent is 5.56ms^{-1} (10.8 knots)

The greater fetch of the eastern Solent (≈30km) gives an added veering component of (3.34 knots) for an average sea breeze flow speed of 4.72ms^{-1} (9.16 knots). This explains how on 04/06/06 the general wind swung from SE to SW or W instead of remaining onshore and may also offer some explanation as to the greater frequency of sea breezes received from the W and SW sectors.

6.0. Conclusions

The Solent sea breeze had an occurrence of 29% over a period of 123 days from May – August 2006.

The most frequent type of sea breeze was found to be the component sea breeze (36.1%) followed by pure (27.8%) and frontal (25%), pseudo sea breezes accounted for the remaining 11.1%.

The relatively close frequencies of component, pure and frontal sea breezes observed suggests that no one type of sea breeze is dominant in the Solent, instead which type of sea breeze that forms is dependant upon conditions before onset. The frequency distribution is without question dominated by the wind climate of southern England.

Earlier observations made by Watts (1987) of the double sea breeze effect were reinforced; it was found that 61.2% of sea breezes flowed up the western Solent and the remaining 38.8% up the eastern Solent. The topography of the Isle of Wight is thought to be responsible for the fact that no sea breezes were observed from the south.

The magnitude of the air-sea temperature difference did not have a bearing upon the time of onset of the sea breeze, however the average air-sea temperature difference revealed that there is a significant difference in the temperature differences required to generate specific types of sea breeze, frontal, pure, component and pseudo sea breezes were found to need on average temperature differences of 4.9, 3.8, 2.7 and 2.7°C respectively.

The time of onset for frontal sea breezes was found to be related to the strength of the offshore gradient wind. If the average wind speed before onset was below 4 knots then onset would be before 11:00, if it was 4-7 knots then onset would be 11:00 – 15:00 and if the average gradient wind was above 7 knots onset was delayed until after 16:00. No offshore winds observed during the study were strong enough to prevent sea breeze formation as a result it is not possible to conclude a maximum wind speed beyond which a sea breeze will not form.

Watts forecast model when reoriented to Calshot was found to be 57% accurate at predicting the time of onset of the sea breeze within one hour, with 75% accuracy to within 1½ hours of the actual occurrence.

The presence of tidal sand and mudflats in the Solent when compared to data from Greenwich lightship give a significantly lower (min = 5.74°C) sea surface temperature in the winter and higher (max = 20.12°C) in the summer. The biggest differences were observed in January (3.31°C) and July (3.1°C). The presence of tidal sand and mudflats in the Solent is thought to shift the “sea breeze season” earlier in the year from February to August opposed to March to October.

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http://www.timeanddate.com: for sun rise and sunset times

http://www.wetterzentrale.de: for past synoptic charts

http://www.xcweather.co.uk/: for up-to-date wind data across the UK